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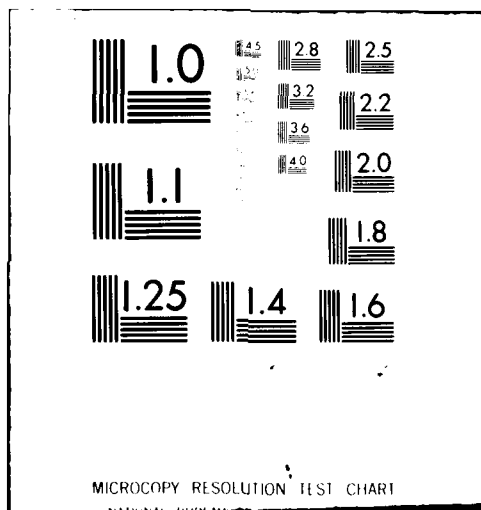
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DELET-TR-78-2990-3



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TACTICAL MINIATURE CRYSTAL OSCILLATOR

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P. Stoermer

**THE BENDIX CORPORATION
COMMUNICATIONS DIVISION
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report describes the advanced development of a fast warmup tactical Miniature Crystal Oscillator (TMXO). The intended use of this TMXO is as a precision frequency/time reference in advanced communications, navigation and position location systems. The present effort is a continuation of work based on the demonstrated feasibility on previous contracts. This interim report describes work performed in evaluation of various aspects of crystals performance, and the contribution of components on oscillator long term stability. Mechanically, progress is described in material selection, process evolution and thermal analysis.		

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1. PURPOSE

The objective of this program is the advanced development of the Tactical Miniature Crystal Oscillator (TMXO) having capability for use as a precision frequency/time reference in advanced communications, navigation, and position location systems.

Previous work conducted under Contracts DAAB07-73-C-0199 and DAAB07-75-C-1327 with The Bendix Corporation has demonstrated the feasibility of a lightweight, low power, fast warmup precision quartz reference oscillator based upon a design which employs the vacuum of the TMXO outer enclosure as an insulating medium. In the TMXO, a thermal control circuit acts to maintain the crystal precisely at its upper turn temperature, providing stable frequency operation. Development is to be conducted to optimize TMXO thermal, electrical, and mechanical design and fabrication processes. These procedures will be established and tests conducted to verify TMXO suitability for use over operating conditions and environments encountered in military manpack, vehicular, and airborne usage. Documentation will detail all aspects of TMXO design, process development, special tooling, and performance testing.

Specifically, the major tasks to be performed on this contract are:

Develop both 5.11 MHz and 10 MHz crystal oscillator circuits to provide an acceleration coefficient and short and long term performance consistent with meeting performance characteristics outlined below. A common hybrid microcircuit design shall be evolved permitting either 5.11 MHz (fundamental) or 10 MHz (fundamental or 3rd overtone) operation with only minor modification during assembly. Precision ceramic flatpack crystal units currently in development by ERADCOM are to be employed.

Optimize TMXO electrical design using computer aided design and analysis methods to provide a high yield in circuit performance and reliability at minimum costs. The analysis is to

show that the TXMO final design will meet performance requirements under worst case element value tolerances and parameter variations.

Develop cost effective processes for fabrication of the TXMO hybrid microcircuit assembly and outer enclosure. Emphasis will be placed on obtaining reliable seals of the inner and outer enclosures which will extend the useful life of the TXMO through reduced power aging.

Design and fabricate special fixturing and tooling for assembly, bakeout, vacuum outgassing, sealing and testing of the TXMO.

Establish TXMO test procedures using Quality Conformance Procedures of MIL-O-55310 as a baseline.

Fabricate and test advanced development models of the TXMO incorporating methods and techniques evolved.

The final report is to contain a technical description of all pertinent design and development work accomplished. It will include a complete description of electrical and mechanical components, processes, procedures and fixturing which would permit reproduction of the developed oscillators.

The required characteristics of the TXMO are given below.

Case Outline. The TXMO shall approximate USAERADCOM outline drawing shown in Figure 1.

Weight. The maximum weight shall be 75 grams.

Seal. The TXMO shall be final baked and solder sealed in a vacuum of 1×10^{-6} Torr. Maximum leak rate shall be 1×10^{-12} ATM-cc/sec.

Supply Voltage. 12 V dc $\pm 5\%$.

Warmup Power. 10.0 watts at any ambient temperature.

Operating Power. After warmup maximum power input not to exceed 250 milliwatts at any temperature.

Power Aging. Not to exceed 1% per month.

Nominal Frequency. The nominal frequency of the TXMO shall be 5.115 MHz and 10 MHz.

Voltage Control. The output frequency deviation for a 0 to 10 V dc change applied at the voltage control terminal shall be no less than 2×10^{-7} . The voltage input impedance shall be greater than 10,000 ohms.

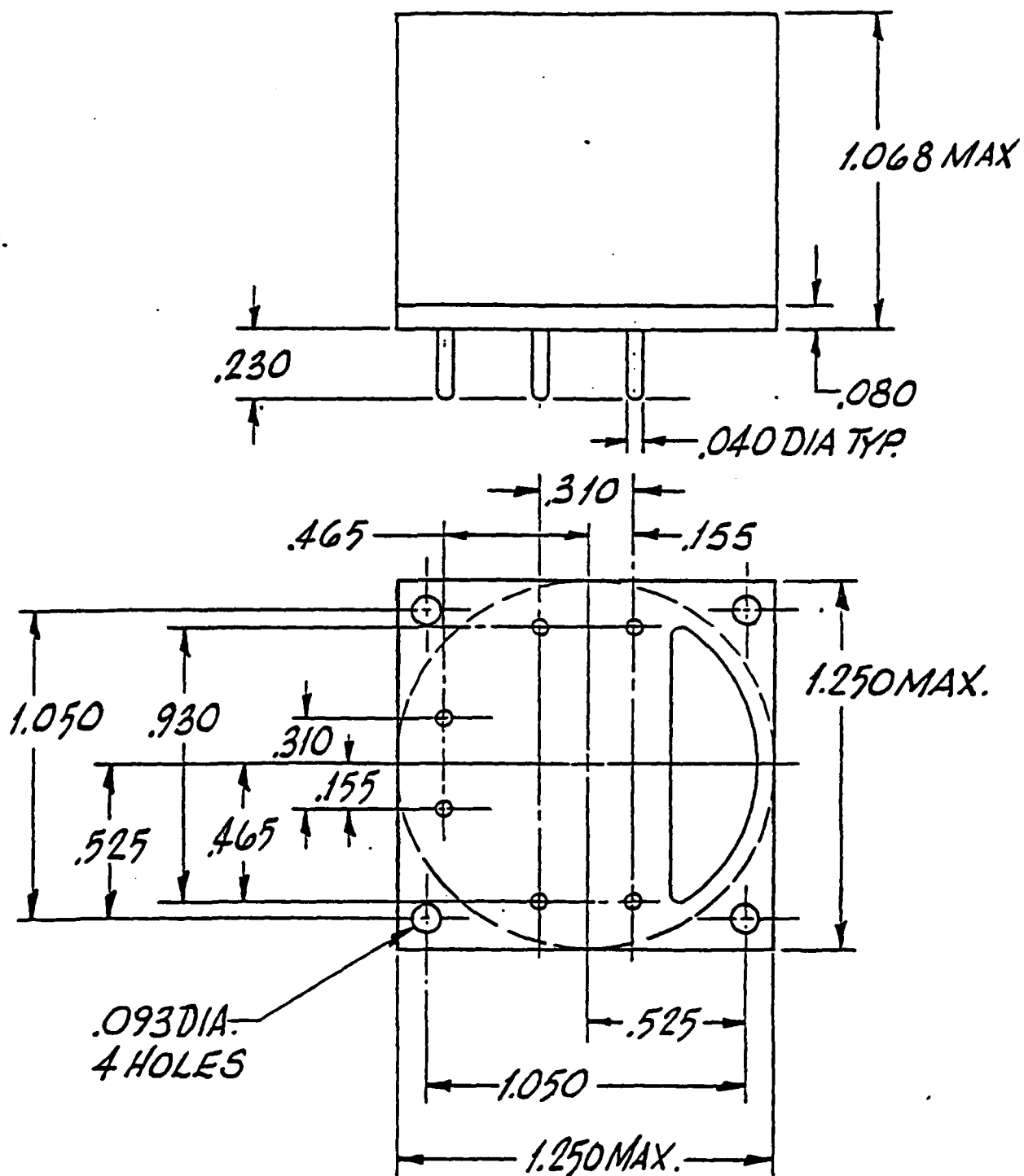


FIGURE 1. OUTLINE DRAWING

Frequency Adjustment. The unit shall be capable of an alternate means of frequency adjustment by termination of the voltage control terminal to ground with a multi-turn 0-100 K ohm potentiometer. The frequency setability shall be better than $\pm 1 \times 10^{-10}$ and tuning range no less than $\pm 1 \times 10^{-8}$ of nominal frequency.

Stabilization Time. Following application of power, the frequency shall be within $\pm 1 \times 10^{-8}$ of final frequency in 3 minutes.

Frequency/Temperature Stability (Steady State). The maximum permissible frequency deviation over the range of -54°C to $+75^{\circ}\text{C}$ shall be $\pm 1 \times 10^{-8}$.

Frequency/Temperature Stability (Transient). The frequency shall not change more than $\pm 1 \times 10^{-8}$ from its initial value when subjected to a positive 10°C amplitude, $1^{\circ}\text{C}/\text{min}$ air temperature ramp starting at -40°C , -5°C , $+30^{\circ}\text{C}$, and $+65^{\circ}\text{C}$.

Frequency/Acceleration Stability. The maximum frequency change measured during static acceleration shall be 1×10^{-9} when tested in accordance with Method 513, Procedure II (helicopter category) MIL-STD-810B. Permanent frequency change shall be no greater than $\pm 1 \times 10^{-9}$.

Frequency/Vibration Stability. The maximum permissible average frequency change measured during and following vibration without isolators shall be $\pm 1.0 \times 10^{-9}$ when tested in accordance with Method 514, Curve M, MIL-STD-810B. The frequency deviation represented by the modulation side bands at the vibration frequency shall not exceed 1×10^{-9} times the peak acceleration level specified for that frequency by curve M.

Frequency/Shock Stability. The maximum permissible frequency change following a shock of 50g. 11 msec shall be $\pm 1 \times 10^{-9}$ when tested in accordance with Method 213, Condition G, MIL-STD-202D.

Frequency/Attitude Stability. The maximum frequency change for a $90 \pm 5^{\circ}$ attitude change in any axis shall be 1×10^{-9} .

Frequency/Altitude Stability. The maximum frequency change following an altitude change from sea level to 10,000 ft shall be $\pm 1 \times 10^{-9}$.

Frequency/Load Stability. The maximum frequency deviation for a load variation of 1000 ohm $\pm 10\%$, 20° phase shall be $\pm 1 \times 10^{-9}$.

Frequency Voltage Stability. The maximum permissible frequency deviation for a supply voltage variation of 12 volts $\pm 5\%$ shall be $\pm 1 \times 10^{-9}$.

Frequency Aging. Aging of the output frequency shall not exceed 2×10^{-10} per week, operating, after a 30 day stabilization period.

Short Term Stability. The maximum rms frequency deviation shall be $\pm 1 \times 10^{-11}$ for averaging times ranging from 1 sec to 20 minutes under conditions of input voltage and ambient temperature controlled to ± 1 mV and $\pm 0.1^\circ\text{C}$ respectively.

Frequency Recovery at -40°C Ambient. The output frequency after warmup during each turn-on period for a 5 cycle frequency recovery shall remain within $\pm 3 \times 10^{-9}$ of the frequency measured on the first cycle. Each cycle shall consist of complete frequency stabilization during turn-on, followed by complete thermal stabilization after power is removed.

Output Voltage. A minimum of 0.170 rms at the output frequency shall be available across an external resistive load of 1 K ohms. The output waveform shall be a sine wave.

Ambient Temperature Range. The TMXO shall meet all requirements of this specification over the ambient temperature range of -54° to $+75^\circ\text{C}$.

Microcircuit Design and Construction. Microcircuit design and construction shall be in accordance with para 3.5 of MIL-M-38510. Exception for use of epoxies for non-electrical connection shall be requested in writing to the contracting office stating type, company experience and inspection and in process controls to be employed.

Quartz Crystal. Ceramic flatpack, microcircuit compatible quartz crystal units in accordance with MIL-C-3098.

Screening. The TMXO microcircuit sub-assembly shall be capable of meeting screening requirements of Method 5008, MIL-STD-883 with the following exceptions:

- a. Bond Strength (para. 3.2.2.1) shall be performed on all units.
- b. Temperature Cycling (para. 3.2.3.4) shall be performed in accordance with test condition B.
- c. Mechanical Shock or Constant Acceleration (para. 3.2.3.5). Constant acceleration only shall be performed.
- d. Omit test procedure 3.2.1.1, 3.2.3.11, 3.2.3.12, and 3.2.3.13.

Metric Dimensioning. Metric dimensioning shall be employed.

Nuclear Survivability. Consideration shall be given to the selection and development of parts, materials, processes, design details, and operating principles to insure realization of the inherent level of nuclear and EMP hardness of which the circuit/sub-system is capable. Typical radiation levels of interest fall in the ranges: 10^2 - 10^5 roentgen (cobalt 60) and 10^{12} - 10^{14} neutrons/cm² (1 MeV equivalent). Test and/or analysis of the design shall be made to indicate the most probable modes of degradation or malfunction and to provide a first order estimate of the degrees of nuclear hardness achieved.

2. ACCOMPLISHMENTS

Planned activities were accomplished during this reporting period, as described below.

2A. ELECTRONICS DESIGN

At the beginning of the second year of the contract, the basic electronic design has been completed, and the substrate layout is under way. The power budget has been verified, which justifies assumptions made previously for the thermal design.

A number of areas of concern are still under investigation, however. Crystal performance is continuously evaluated as new units are delivered. The major parameters under study include short term stability, aging rates, tuning accuracy, turn temperature accuracy, and attitude stability.

Another area of concern includes component contribution to the long term stability of oscillator frequency. Various types and sources of supply of chip capacitors are under investigation. The noise current produced in thick film resistors is also being studied, and lower noise thin film devices may be utilized in critical applications of the thermal control circuit.

Finally, methods and processes are being developed; for example, a test strategy for selecting tuning capacitor values and resistance values for the thermal control circuit.

The work performed in these areas will now be described in some detail.

(1) CRYSTAL EVALUATION

(1.1) Short Term Stability of 10 MHz Third Overtone Crystals

The short-term stability of several of the 10 MHz third overtone crystals was measured, with results shown in Figure 2a and Figure 2b. The measurement compared the oscillator frequency with the 5 MHz computing counter clock multiplied

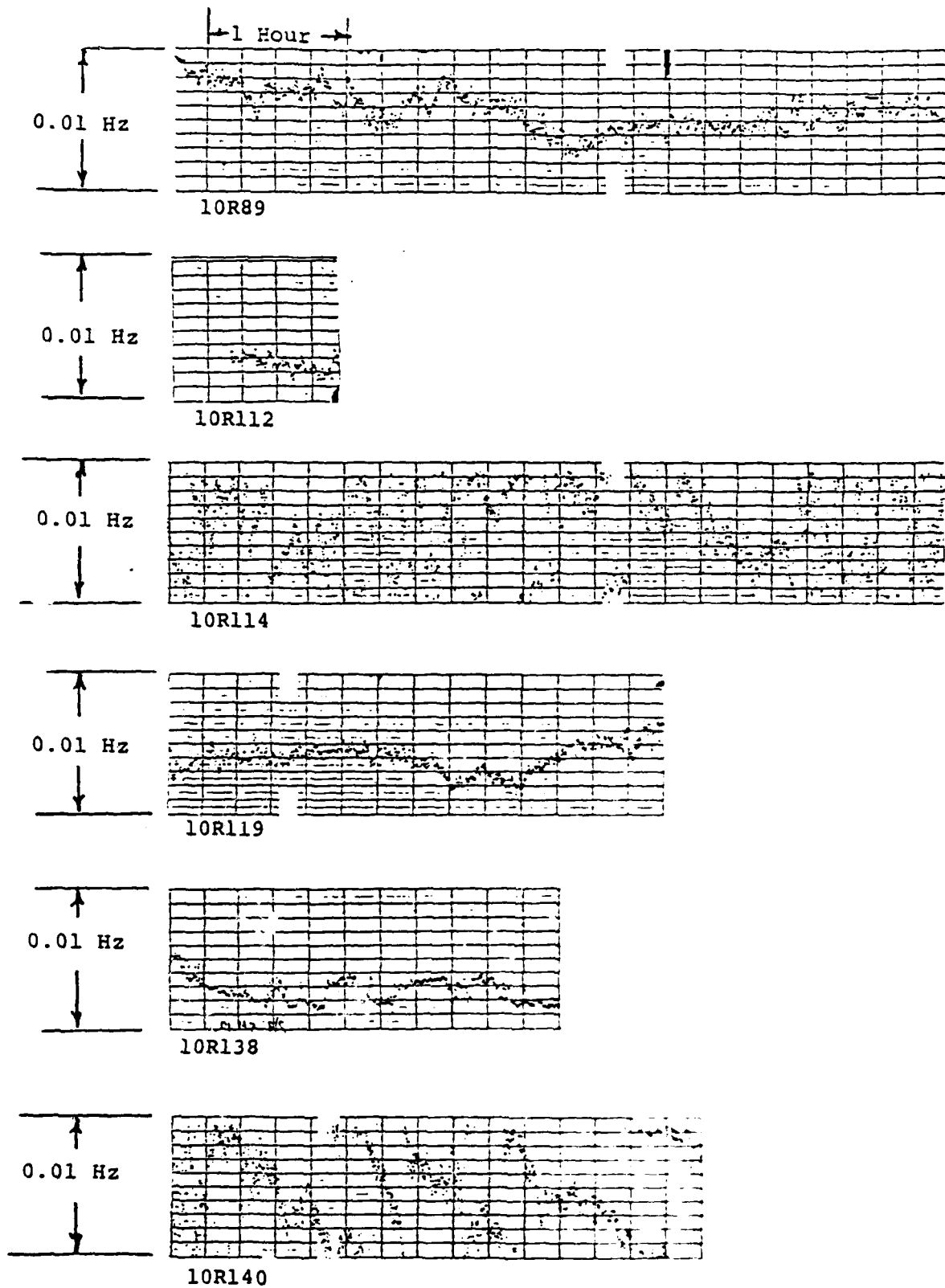


FIGURE 2a.

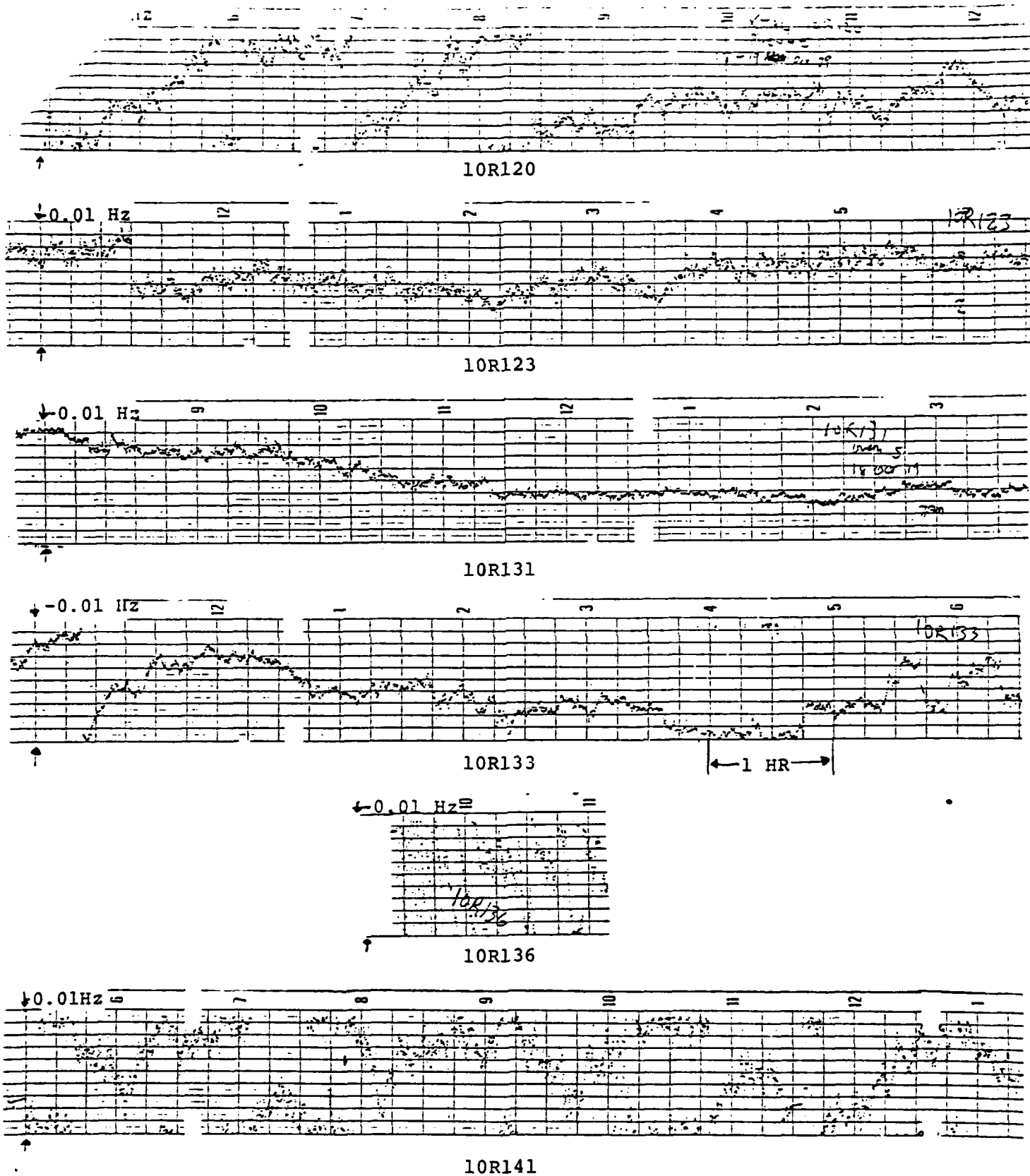


FIGURE 2b.

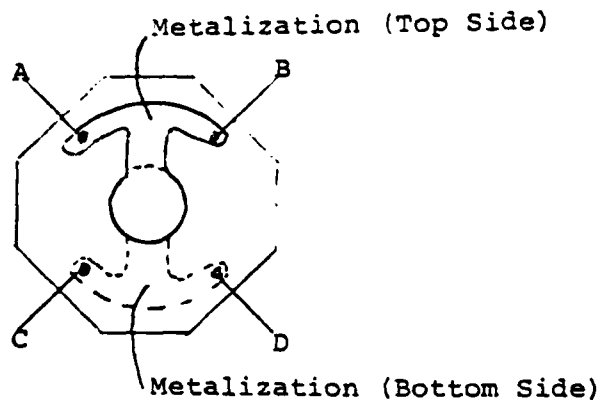


TABLE I

CRYSTAL NUMBER	R_{ab}	R_{cd}	R_s (G.E.N.D.)
CR173	3.82 Ω	5.88 Ω	-
CR175	4.31 Ω	14.60 Ω	-
CR186	2.90 Ω	5.80 Ω	-
CR194	2.75 Ω	3.10 Ω	5 Ω
CR197	1.78 Ω	3.39 Ω	6 Ω
CR205	2.38 Ω	2.58 Ω	-
CR209	2.19 Ω	4.28 Ω	
CR213	2.41 Ω	3.49 Ω	4 Ω
CR217	2.65 Ω	3.15 Ω	5 Ω
CR223	2.93 Ω	4.10 Ω	5 Ω
CR226	2.80 Ω	12.0 Ω	8 Ω
CR233	2.93 Ω	2.98 Ω	6 Ω
CR234	2.55 Ω	4.82 Ω	6 Ω
CR235	1.93 Ω	2.30 Ω	4 Ω
CR237	2.82 Ω	2.92 Ω	5 Ω
CR238	2.39 Ω	4.43 Ω	5 Ω
CR240	2.51 Ω	2.67 Ω	6 Ω
10R89	3.47 Ω	8.98 Ω	-
10R112	2.78 Ω	3.50 Ω	22 Ω
10R114	5.06 Ω	10.39 Ω	24 Ω
10R119	2.41 Ω	3.74 Ω	18 Ω
10R120	2.58 Ω	4.43 Ω	21 Ω
10R123	1.87 Ω	3.47 Ω	17 Ω
10R126	2.66 Ω	2.71 Ω	21 Ω
10R131	2.15 Ω	5.2 Ω	21 Ω
10R134	2.62 Ω	3.12 Ω	21 Ω
10R135	2.81 Ω	2.93 Ω	-
10R136	2.11 Ω	2.60 Ω	17 Ω
10R138	3.22 Ω	3.29 Ω	22 Ω
10R140	2.40 Ω	2.85 Ω	20 Ω
10R141	2.29 Ω	2.36 Ω	15 Ω
10R145	2.38 Ω	2.39 Ω	16 Ω

by two. The vertical (frequency) scale is 0.01 Hz full scale, and the horizontal (time) scale is 1 hour per inch. None of the 10 MHz third overtone crystals evaluated so far have demonstrated acceptable short term stability.

(1.2) Crystal Terminal Resistance Measurements

Large variations in resistance values have been measured between adjacent terminals of the crystal package for the units presently on hand. In the figure, terminals A and B are connected to the metalization on one side of the quartz wafer, while terminals C and D are connected to the metalization on the other side. Resistance readings were made between terminals A and B, and between terminals C and D. Table I gives measured values and the effective series resistance measured at G.E.N.D.

In some cases, by shorting adjacent terminals externally, a reduction of the effective series resistance as indicated on the CI meter was noted, but an improvement in short term stability was not generally obtained. The relatively high resistance values are understood to be the result of inadequate deposition of the electroding material and is correctable on later units.

(1.3) Crystal Aging Rate Versus Drive Levels

The dependence of crystal aging rate on excitation amplitude had been determined for crystal CR 186, where essentially no change in aging rate was observed for operation at 0.7 ma and 50 μ amp.

The same result has now been obtained for crystal CR 212. Previous rates from 1.0 to 1.2×10^{-10} /day have been noted for 0.5 ma crystal current levels. A new run of over 2 weeks duration with 100 μ amp level averaged 1.07×10^{-10} / day aging rate.

(1.4) Amplitude To Frequency Effect Of Fundamental Crystals

The "no-reactance" oscillator circuit was used to determine the amplitude to frequency effect of one of the fundamental crystals (CR 205). The results are shown in Figure 3. The amplitude to frequency effect for 5 MHz fifth overtone crystals has been reported to approximate the relation:*

$$\frac{\Delta F}{F} = Di^2$$

where D = a constant = 2×10^{-7}

i = crystal current in milliamps

This relation has also been plotted in Figure 3.

The contribution of the oscillator itself was estimated by measuring amplitude to frequency effect with LC elements replacing the crystal, calculating the equivalent oscillator phase increment, and then calculating the frequency increment at the crystal to correct for this phase change. The estimated oscillator contribution was about 4% of the measured crystal amplitude to frequency effect.

For the TMXO, the operating point is near 0.2 ma crystal current, where the magnitude of the amplitude to frequency effect is less than 1×10^{-8} .

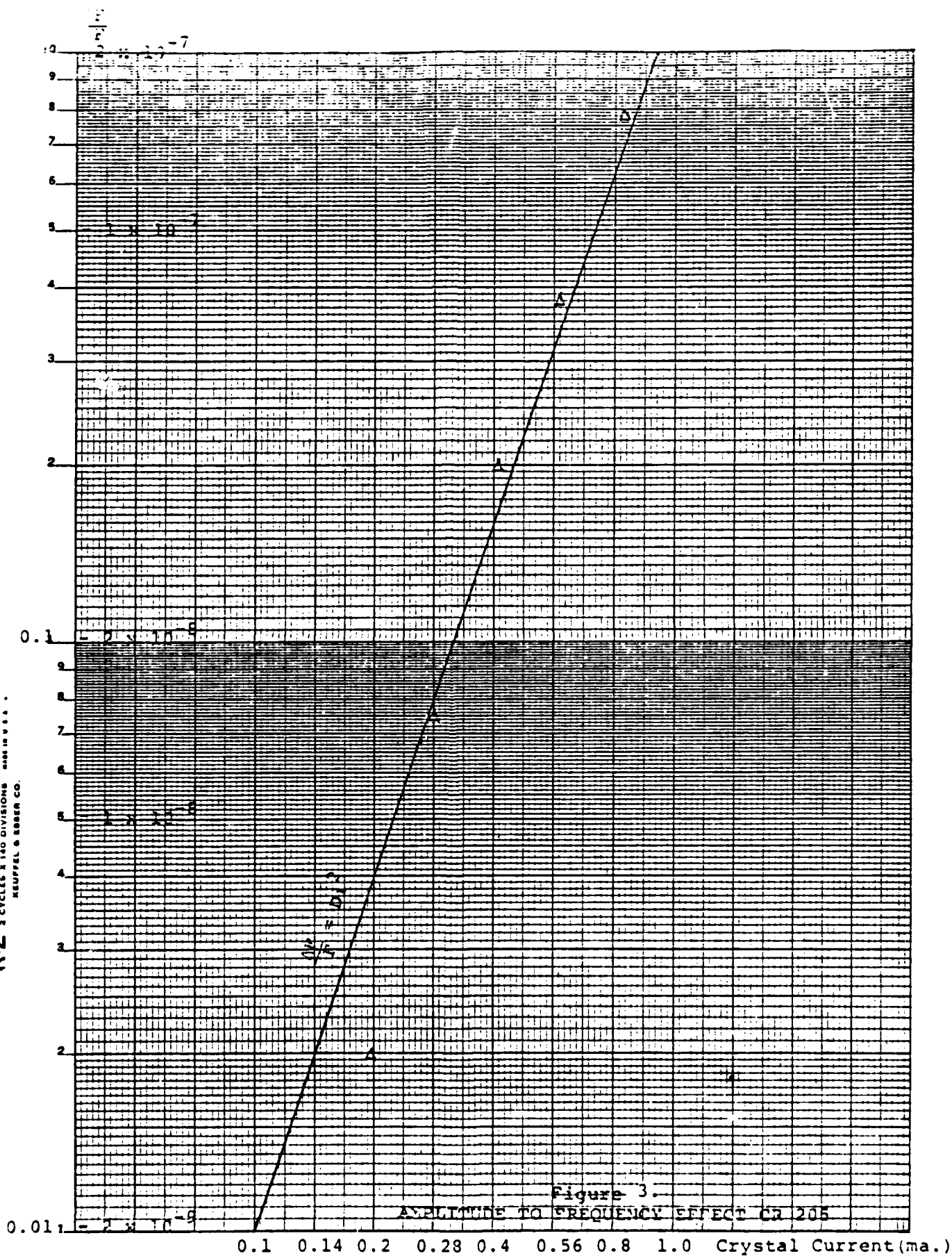
(1.5) Crystal Frequency/Acceleration Stability Measurement

The detuning effect of the force of gravity has been measured by the turnover method on a few of the 5.115 MHz fundamental mode crystals as follows:

CRYSTAL	$\frac{\Delta F}{F}$	SENSITIVITY TO ACCELERATION
CR186	$\frac{\Delta F}{F} = 1 \times 10^{-8}$	per G
CR212	$\frac{\Delta F}{F} = 1 \times 10^{-8}$	per G
CR6R9	$\frac{\Delta F}{F} = 1.7 \times 10^{-8}$	per G

*"Stability of Standard Frequency Oscillators," G.R. Experimenter, Vol. 38, No. 6, p.4, June 1964.

K·E SEMI-LOGARITHMIC 46 5133
2 CYCLES X 140 DIVISIONS
NEUPPEL & EBER CO.



For comparison, Bliley number 28695 measured

$$\frac{\Delta F}{F} = 0.75 \times 10^{-8} \text{ per G.}$$

This crystal consists of a 5.115 MHz fundamental blank furnished by ERADCOM and assembled by Bliley into their 61BGAH-5S package.

Also tested was Bliley 5th overtone 5 MHz crystal in our FTS B-5400 reference oscillator which measured

$$\frac{\Delta F}{F} = 1.3 \times 10^{-9} \text{ per G, and the clock in our H.P. Computing Counter which measured } \frac{\Delta F}{F} = 1 \times 10^{-9} \text{ per G.}$$

(2) COMPONENT EVALUATION

(2.1) Drift Contribution of Porcelain Chip Capacitors

Measurements made during the previous six month interval of this program had indicated excessive drift would be introduced into the frequency stability performance of the fundamental oscillator by the measured aging of the porcelain chip capacitors used for matching and loading the crystal. The rates were generally near -2 ppm./day for the ATC-100 units tested.

The effect of the crystal load capacity and finishing tolerance was reviewed to relate finishing tolerance to capacitor induced aging. In reducing the effect of capacitor aging on oscillator long term stability, the load capacitance value should be as large as possible, as illustrated by the relation:

$$\frac{\Delta F}{F} \bigg/ dt = \frac{C_1}{2C_L} \times \frac{\Delta C_L}{C_L} \bigg/ dt, \text{ where}$$

$$\frac{\Delta F}{F} \bigg/ dt = \text{time rate of change of fractional frequency}$$

$$C_1 = \text{crystal motional capacity}$$

C_L = load capacity

$\frac{\Delta C_L}{C_L} / dt$ = time rate of change of fractional load capacity

The effect of finishing tolerance ($\Delta F = \pm KF$) is to cause values of load capacity smaller than the maximum value $C_{L_{\max}}$

to be used with the lower frequency units, with resulting higher drift rates given by:

$$\left. \frac{\Delta F}{F} / dt \right|_{\max} = \left(\frac{C_1}{2C_{L_{\max}}} + 2K \right) \frac{\Delta C_L}{C_L} / dt$$

For the present fundamental crystal design

$$C_1 = 0.011 \text{ pf}$$

$$C_{L_{\max}} = 110 \text{ pf}$$

$$K = 5 \times 10^{-6}$$

and, with the porcelain dielectric capacitors,

$$\frac{\Delta C_L}{C_L} / dt = 2 \text{ ppm/day}$$

so that $\left. \frac{\Delta F}{F} / dt \right|_{\max} = 1.2 \times 10^{-10} / \text{day}$ due to the capacitors alone.

This rate is over 4 times the allowed oscillator rate of $2 \times 10^{-10} / \text{week}$.

The relation for $\left. \frac{\Delta F}{F} / dt \right|_{\max}$ is plotted Figure 4 for

the fundamental crystal, with larger values for $C_{L_{\max}}$ and

various values of finishing tolerance. It appears that to achieve fractional frequency stability of less than $3 \times 10^{-11} / \text{day}$

OSCILLATOR DRIFT RATE

Due to Capacitor Rate of 2ppm/day

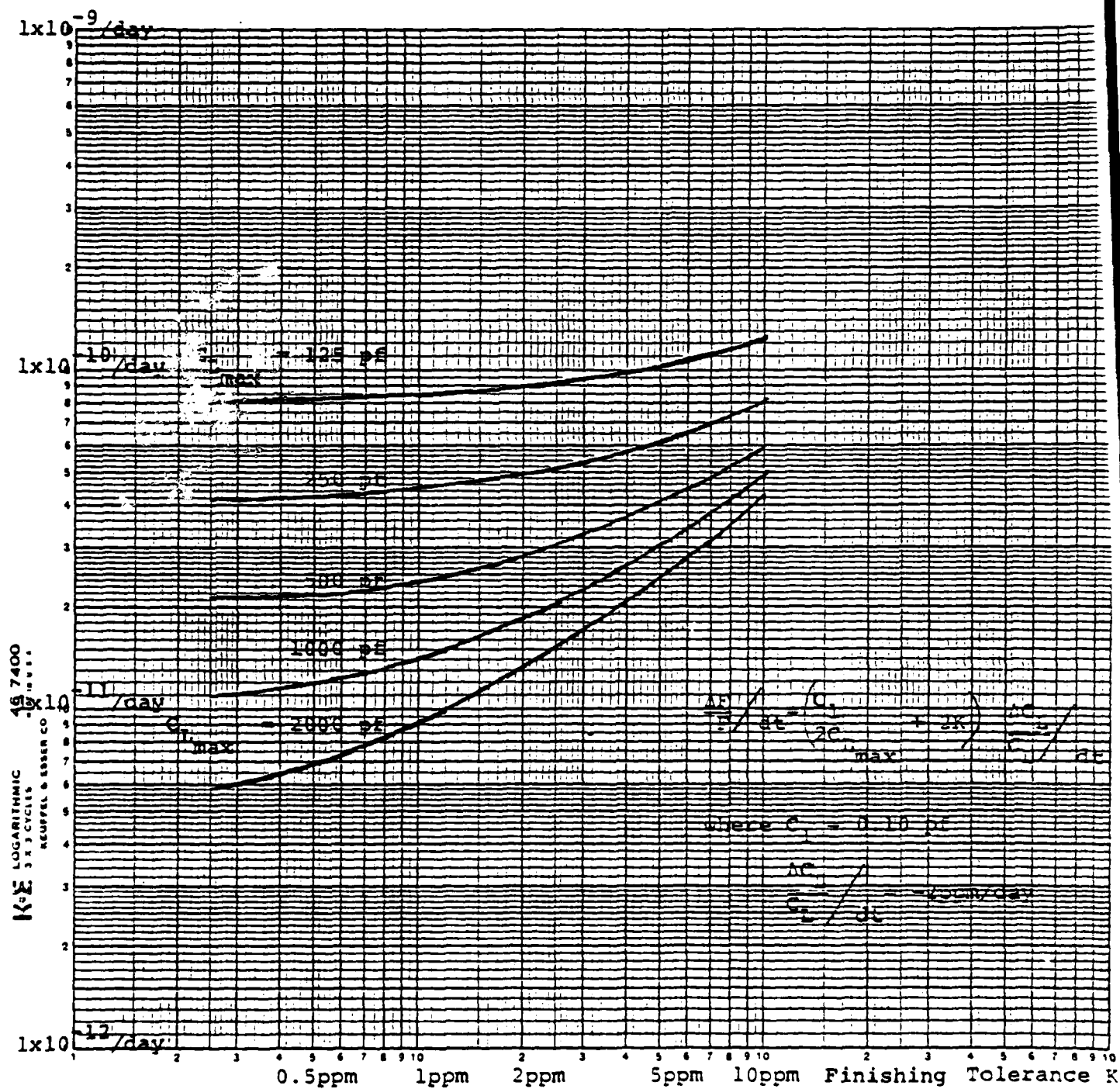


FIGURE 4. OSCILLATOR STABILITY FUNCTION

(2×10^{-10} /week), it will be necessary to both increase $C_{L_{max}}$ and decrease the finishing tolerance over the present design. For the present, these improvements in crystal finishing tolerances are not attainable and further effort has been directed toward finding more stable capacitors.

A 110 pf porcelain dielectric chip capacitor manufactured by Dielectric Laboratories, Inc. was evaluated for long term drift by noting the change in drift rate of an oscillator when the capacitor was introduced in series with the crystal (CR212). The aging rate increased from 1.1×10^{-10} /day without series capacitance to 2.4×10^{-10} /day with the test capacitor installed. The calculated capacitance stability is -2.6 ppm/day.

In another test, an ATC 100B (110pf) capacitor was introduced in series with crystal CR 186, and the drift rate reduced from about $+2 \times 10^{-10}$ /day without capacitor, to a value of about $+0.5 \times 10^{-10}$ /day as shown in figure 5. The calculated capacitor fractional stability was +4 ppm/day. In several previous measurements ATC capacitors had generally shown fractional capacitor stabilities near -2ppm/day. In the measurement described in figure 5, the capacitor had been taken from a recently procured lot, and had been mounted to a small section of substrate using a non-conducting epoxy in the manner to be employed in the TMXO.

Figure 6 shows aging data taken with crystal CR 212 in a "no reactance" oscillator without series capacitor. The average rate is close to 1.0×10^{-10} /day. A MA 24-111J (110pf) porcelain chip capacitor manufactured by JFD was then installed in series with the crystal, and aging data taken as shown in figure 7. The difference in aging rate appears quite small, indicating a negligible capacitor drift contribution. In a subsequent measurement, the same capacitor was mounted to a

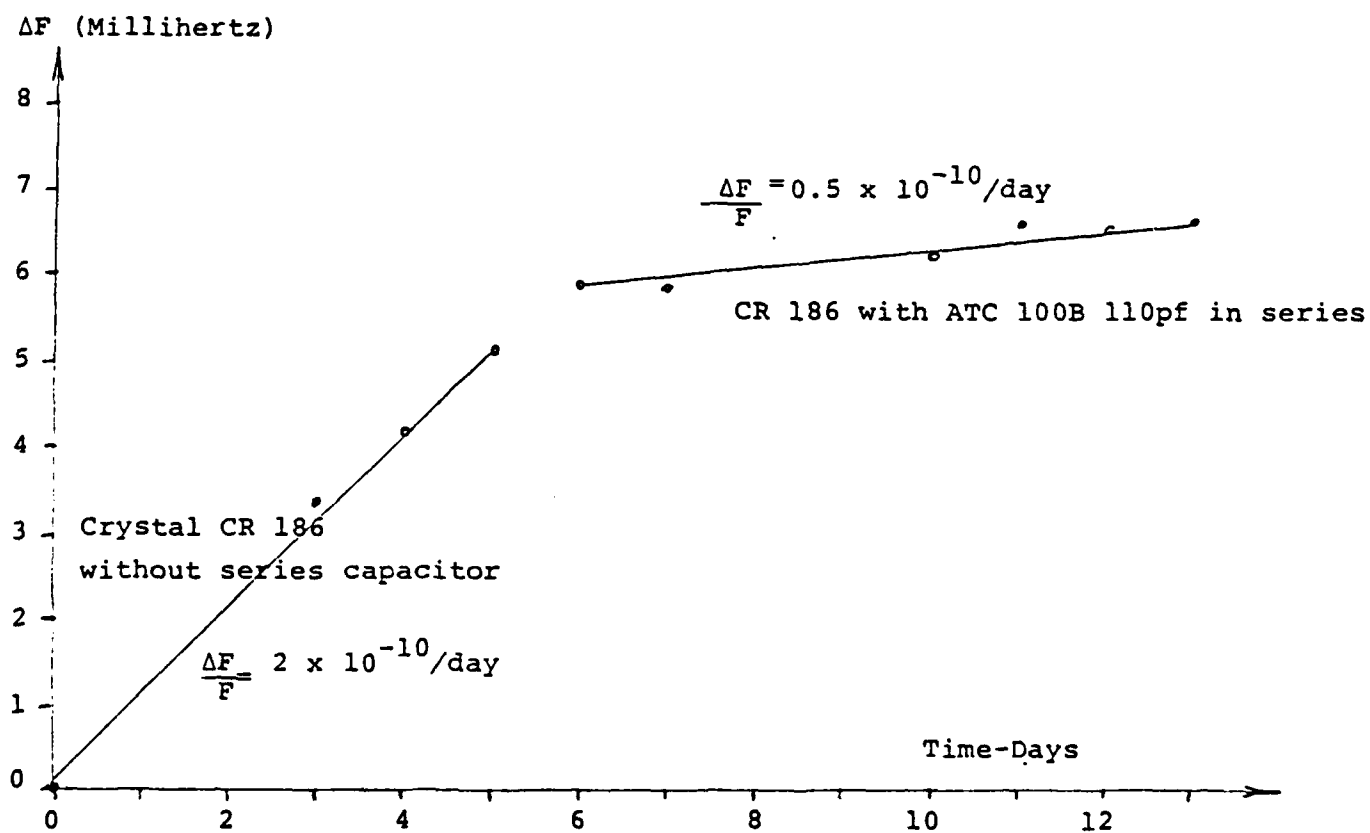


Figure 5

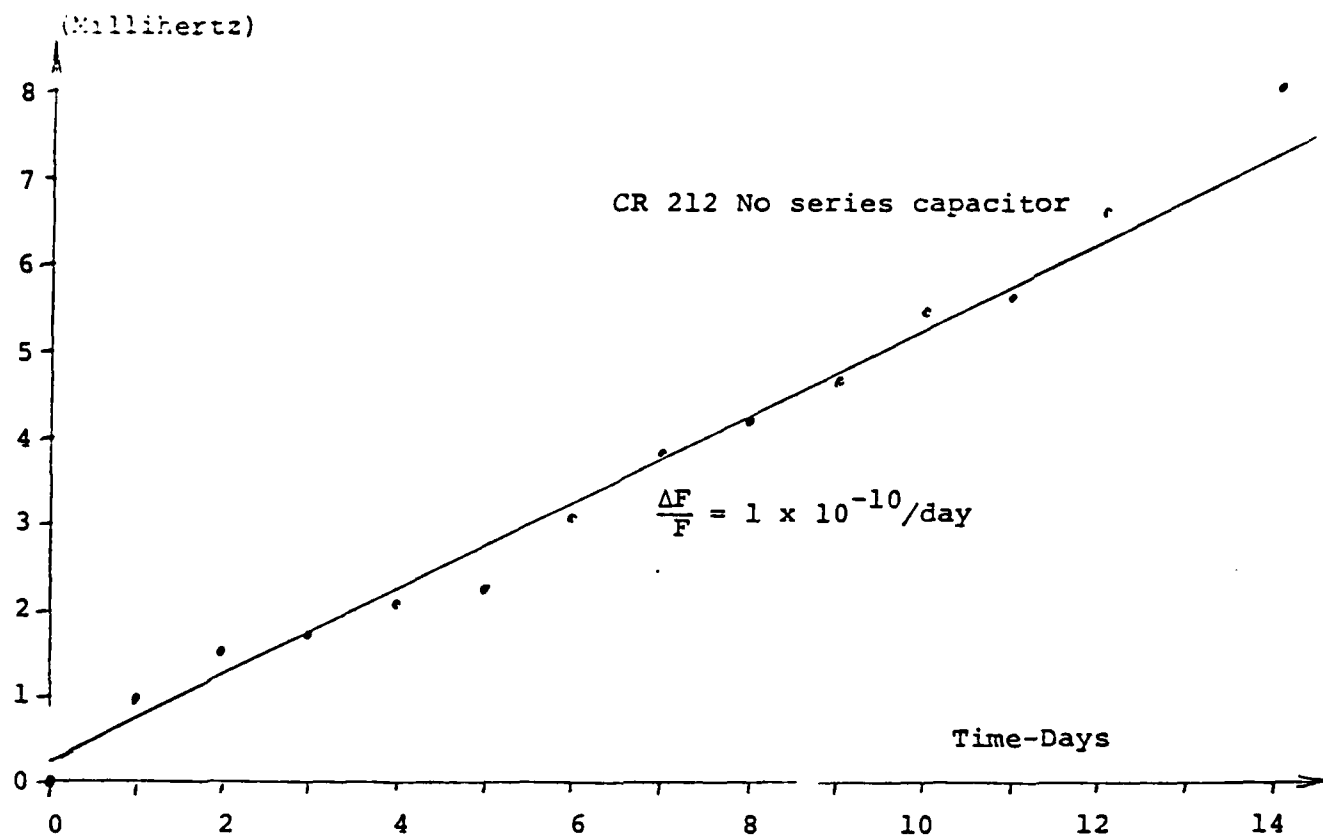


Figure 6

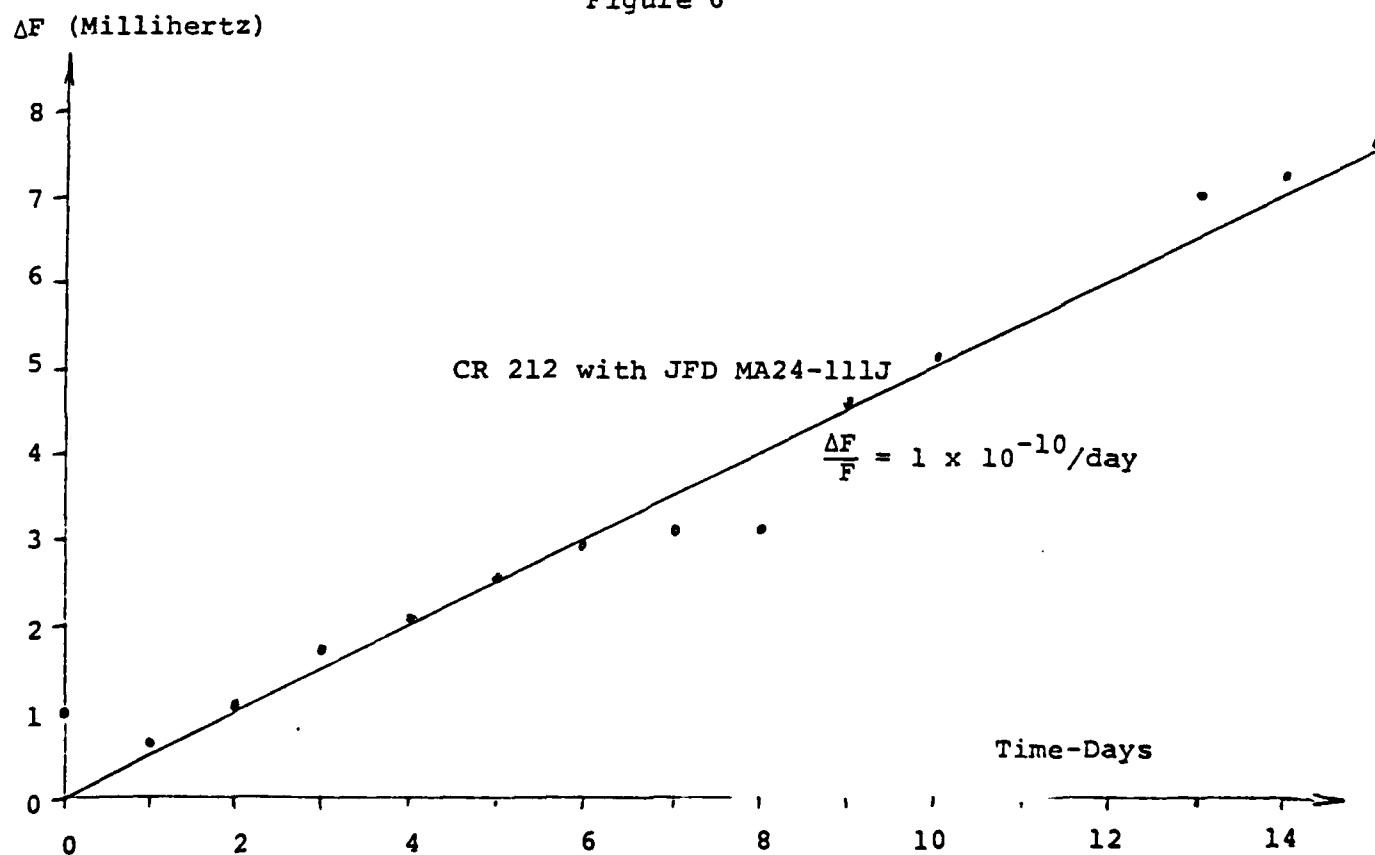


Figure 7
-19-

small section of substrate using ABLESTIK 74-1 non-conducting epoxy, and the capacitor again installed in series with CR212. The long term aging rate of the oscillator was maintained near 1×10^{-10} /day rate, indicating that the use of the epoxy for mounting the porcelain dielectric tuning capacitors does not affect crystal oscillator long term stability.

(2.2) Aging of Alternate Dielectric Type Capacitors

Measurements have also been made on alternate dielectric type capacitors to compare with the porcelain units. Figure 8 shows the results obtained with silver mica (part number EMCM05FD101J03) and glass (part number CGWCY10C111J) capacitors introduced in series with crystal CR 212. After 5 days the mica capacitor fractional capacitance stability was about -30 ppm/day, while the glass capacitor stability was about -70 ppm/day. These results show the porcelain units to be at least an order of magnitude better than the alternate types investigated so far.

(2.3) Aging of Coil Used With Overtone Crystals

The aging characteristic of a candidate coil design for the 10 MHz third overtone oscillator has been evaluated. By introducing the coil in series with crystal CR212 in our test oscillator, the aging rate was found to increase from 1.2×10^{-10} /day to 1.4×10^{-10} /day. The calculated coil aging rate is -2ppm/day for the nominal 2 μ H coil.

The contribution of this coil aging to the 10 MHz third overtone oscillator aging has been calculated as approximately 5×10^{-12} /day which is less than one fifth of the specification drift rate for the oscillator and is considered acceptable.

In summary, it appears difficult to meet the aging specification of the fundamental oscillator with present finishing tolerances and load capacity values. The requirement on the

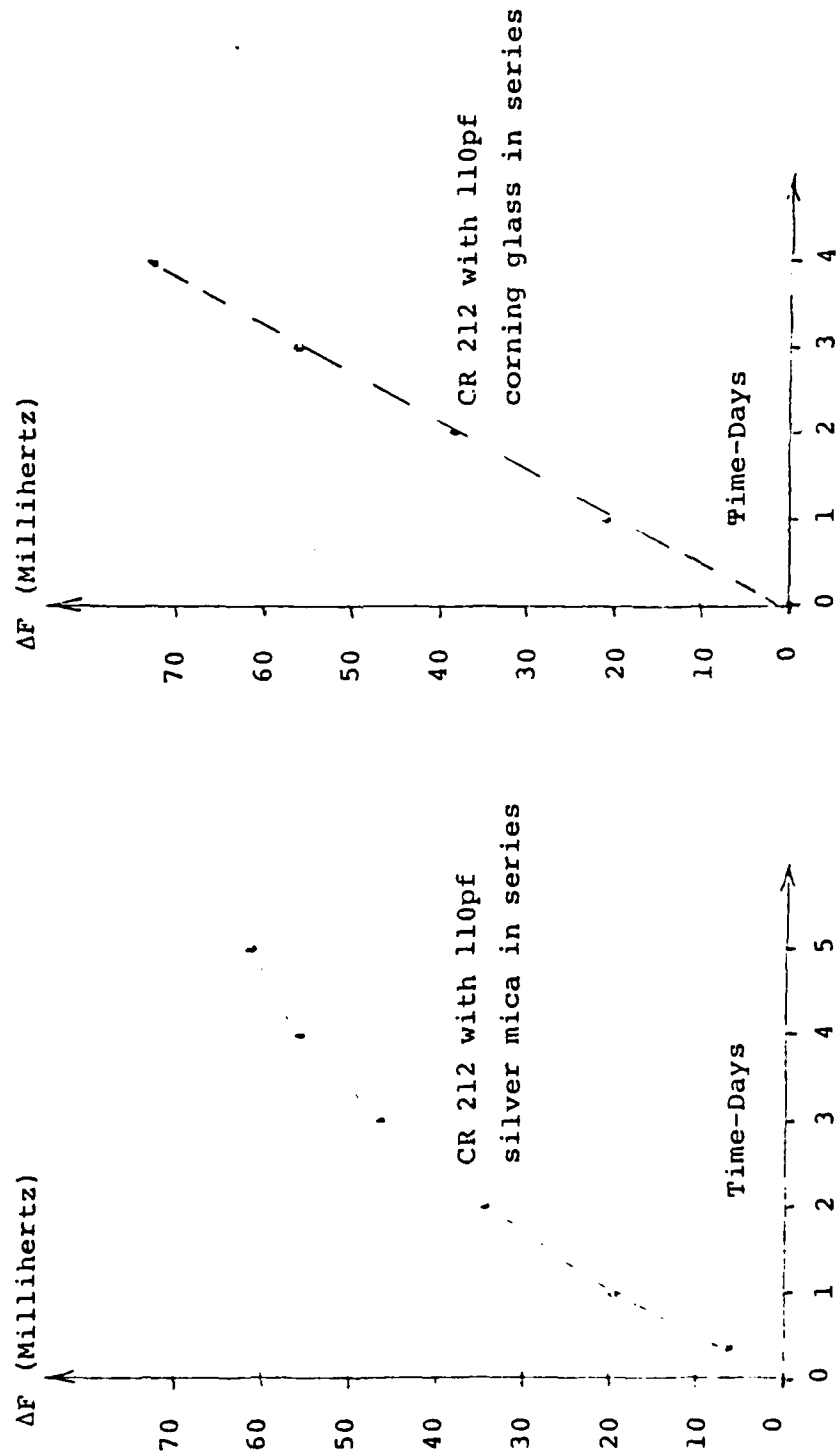


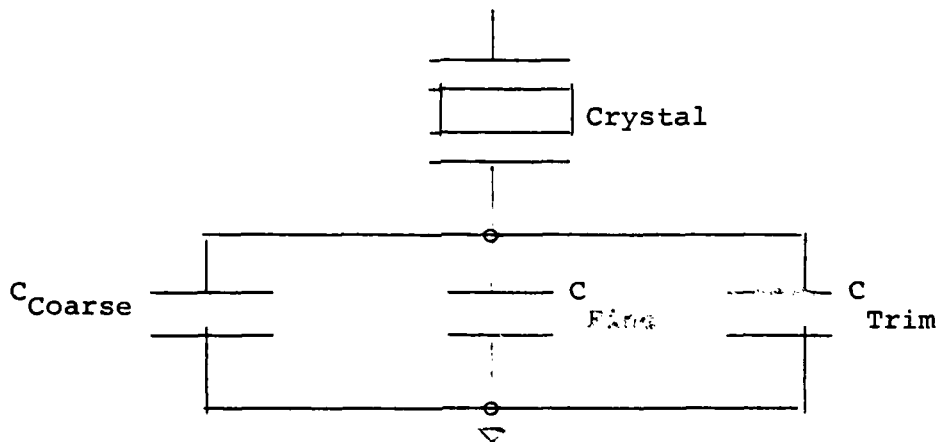
Figure 8

capacitors could be relaxed somewhat by tighter crystal tolerances. More of the porcelain chip capacitors (JFD MA 24-111J) should be evaluated to determine realistic stability performance values. The third overtone design does not appear to be degraded by the requirement for the addition of the coil.

3. CIRCUIT DESIGN

(3.1) Oscillator Tuning Provisions

Details of the tuning method for the 5 MHz fundamental and 10 MHz third overtone oscillators are to be described. The loading capacitance to be added in series with the crystal circuit is to be implemented by selecting fixed porcelain dielectric capacitors from two groups and connecting them in parallel with a small range porcelain dielectric trimmer as indicated below.



Based on crystal finishing inaccuracies of 5ppm, the range of variation to be accommodated in the two oscillators is:

<u>Oscillator</u>	<u>Required Range of Capacitance</u>
5 MHz	136 pf to 191 pf
10 MHz 3rd O/T	33.5 pf to 90.5 pf

The trimmer capacitor, to be procured from American Technical Ceramics, allows selection of 0 to 4.25 pf in 0.25 pf steps by wire bonding to appropriate sections of the termination. The group of "FINE" values consists of 7 sizes spaced in approximately 2 pf increments to 20 pf. The group of "COARSE" values consists of 6 sizes spaced in approximately 20 pf increments for the 5 MHz fundamental oscillator, and 4 sizes spaced in approximately 20 pf increments for the 10 MHz 3rd overtone oscillator.

The trimmer increment of 0.25 pf corresponds to a $\frac{\Delta F}{F} = 1 \times 10^{-7}$ increment for both oscillators.

Selection of the values of coarse and fine capacitors required to tune an oscillator is made by mounting the crystal and oscillator substrate on a carrier board which is installed within a test oven. The circuit is configured with the crystal return lead temporarily connected to a varactor on the carrier board. The varactor has previously been calibrated for capacity versus voltage at temperatures near the crystal upper turn temperature.

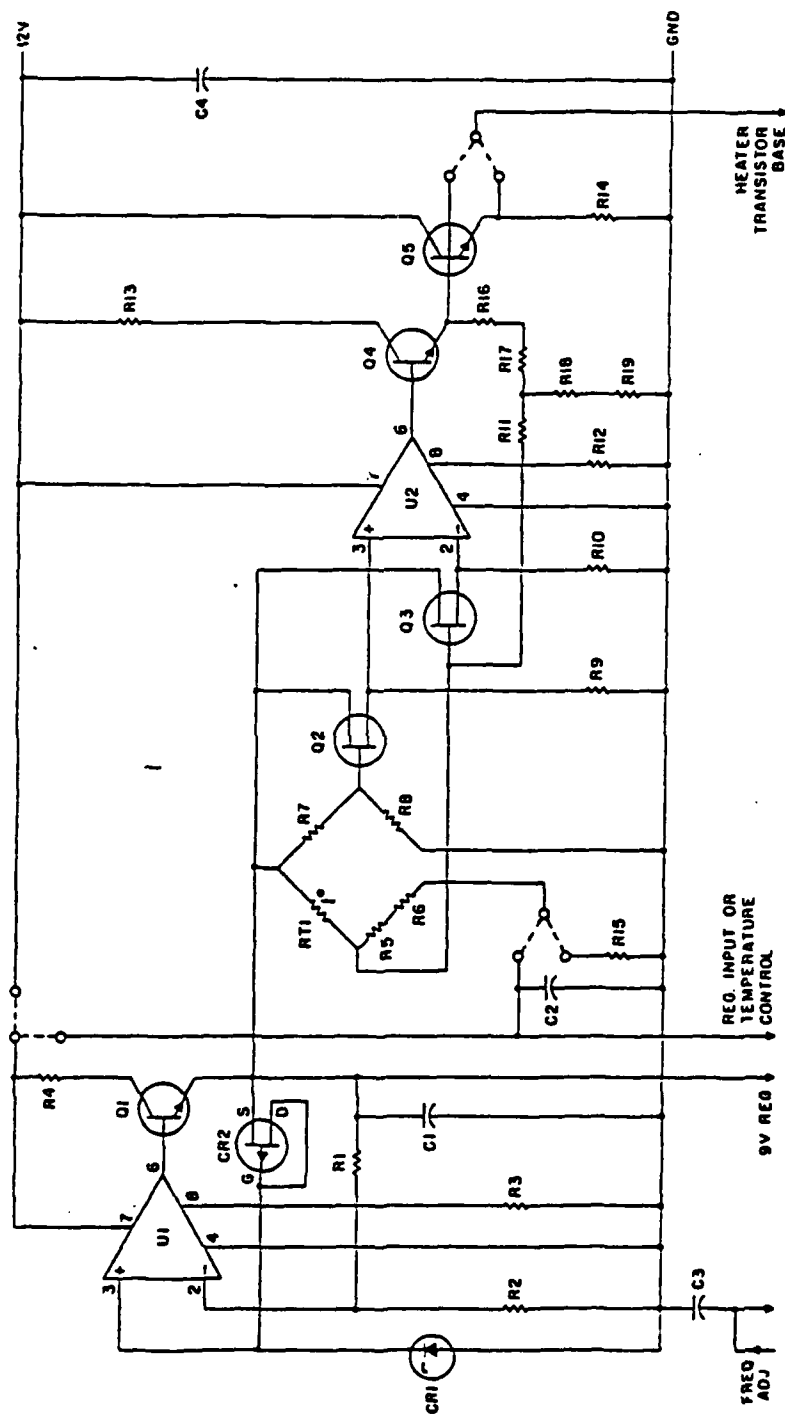
The temperature of the oven is then swept through the expected turn point of the crystal at rates of $\pm 20^\circ/\text{hour}$, and the frequency versus temperature recorded. The apparent temperatures of the frequency minima during heating and cooling are averaged, and the process repeated at slower sweeps of about $1^\circ/\text{hour}$ around the previously determined average temperature. The oven temperature is finally set to the slow-sweep average temperature and the varactor voltage adjusted to bring the oscillator to the desired frequency. The coarse and fine capacitors are then selected to provide the capacitance corresponding to the varactor capacitance at the voltage determined above. The trimmer allows adjustment within steps of the fine tuning capacitor.

(3.2) Temperature Control/Voltage Regulator Substrate Design

There have been no major changes in the temperature control and voltage regulator circuit from that previously reported. However, some additional features have been added to the circuit and substrate layout which will allow the gain of the temperature controller to be adjusted and also to allow the power source for the heater to be separate from the power source for the oscillator electronics.

The provision for gain adjustment in the temperature controller is a temporary expedient which will be convenient in optimizing the prototype units but should not be necessary in production units. The option for separating the heater supply from the oscillator electronics will be useful in applications where it is desirable to operate the heater from an unregulated supply such as a battery. In order to provide this capability without redesign of headers and support structure, the lead originally intended to provide external trimming of temperature would be utilized for the regulator input by a choice of the location of a jumper. In this case the jumper connecting C2 to R4, U1-7 as shown in Figure 9 would be installed, while an internal temperature control trimming resistor R15 would be employed by selecting the jumper location R6 to R15. For the original single supply concept, the regulator would be powered from the 12 volt input by jumpering this input to R4, and U1-7, and provision for the external temperature trimming resistor selected by jumping R6 to C2. The external version of R15, located in the TMXO base would then be connected from the temperature control lead to ground.

As mentioned previously, the resistors R1 and R2 which establish the voltage regulator output level are to be implemented as thin film devices, to minimize regulator output



Voltage Regulator & Thermal Control Circuit

Figure 9

noise. The device chosen for R2 can be adjusted by wire-bonding jumpers across series connected resistor elements to allow close control of output voltage. By selecting regulator output about 8.5 VDC, the regulator should accommodate input levels down to 10 VDC.

Since it has not been possible to accurately determine the thermal control stability performance prior to assembly of the prototype, a number of parameter value adjustments have been incorporated in the substrate to provide control of the stability as follows. The resistor network consisting of thick film resistors R16 through R19 will allow gain adjustment of about 15 dB in 1.5 dB steps by combinations of jumpers across individual resistors.

Also, the physical position of the thermistor on the substrate is selectable in the radial dimension. Heat sources Q5 located at the center, and R14 which is constructed in a circular configuration around Q5, occupy the central area to about one third of the substrate radius. The thermistor location in the radial dimension is expected to have an impact on the degree to which the controller maintains constant crystal temperature with ambient temperature variations. The spacing, and therefore, time lag between temperature of the heater transistor and thermistor temperature is expected to influence the control loop stability. The ability to adjust thermistor location and circuit gain should allow performance optimization without major changes of substrate layout.

Finally the capability was incorporated to select, by jumper position, the source of drive for the heater transistor employed on the oscillator substrate. By jumpering its base to Q5 emitter, the oscillator substrate heater would function only during warm-up, and would not contribute to steady state loop stability. By connecting both heater transistor bases together, symmetrical heating of the crystal should be provided.

2B. MECHANICAL DESIGN SUMMARY

Work has continued on the conceptual approach described in the last semi-annual report. The overall concept and cross-section is illustrated in Figure #10. Essentially, the mechanical design consists of two enclosures, one housed within the other. A vacuum between the enclosures minimizes oscillator power consumption and maintains a stable operating temperature when environmental conditions change. The microelectronics are housed in the internal enclosure which is backfilled with dry nitrogen and hermetically sealed. This electronics package is then supported in the vacuum enclosure by wires and a mica bridge. Maintenance of vacuum is provided by a getter.

Efforts this reporting period have concentrated in the areas of material acquisition and evaluation, hermetic sealing and vacuum investigations, assembly process development, heat transfer analysis, vibration testing, and construction of the first prototype TMXO. Firm hardware commitments have been made during this reporting period. When necessary, minor design changes have been implemented to correct problems discovered.

(1) MATERIAL ACQUISITION AND EVALUATION

HEADERS

Both of the header designs utilize Kovar as the base material. Either glass or ceramic may be used as insulators for hermetic feedthroughs. Airpax in Cambridge, Maryland had been contracted to provide ceramic feedthroughs for TMXO's headers. The Kovar plates were machined to configuration by Bendix then sent to Airpax for brazing the ceramic feedthroughs. All the headers were determined to be gross leakers: a pressure of 1×10^{-4} Torr could not be held. Also, the .018 inch diameter Kovar wires

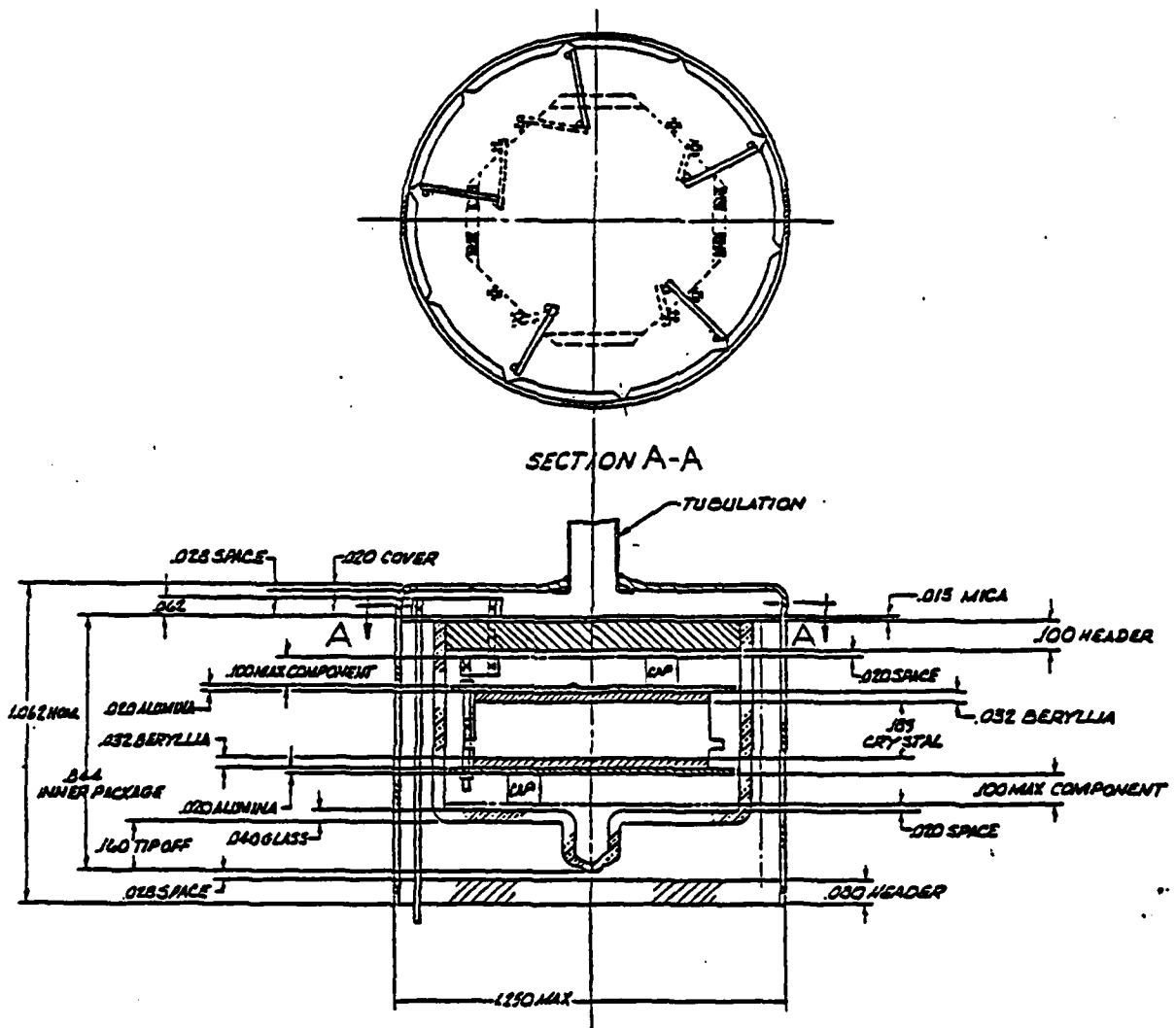


FIGURE 10. OVERALL CONCEPT

annealed during the braze cycle and were useless in supporting the internal package. A decision was then made to continue feedthrough work at Airpax using Corning glass #7052. Headers with glass feedthroughs were received from Airpax and leak tested. Leak rates were less than 1×10^{-8} STD CC/SEC. While work was continuing at Airpax, another company, Hittman Materials and Medical Components, Inc. was contracted to design and fabricate TMXO's ceramic feedthrough headers. A new approach using stainless steel tubes as the support wires was unsuccessful. Annealing of the stainless steel occurred while brazing. As a result, a material search was conducted to identify a high temperature, high strength wire with nearly the same thermal characteristics of Kovar. Inconel alloy 625 was chosen and will be used in the new vacuum header design.

ENCLOSURES

Tooling for hydroforming the two Kovar enclosures has been completed and parts received. A worst case tolerance analysis of the TMXO assembly was performed to determine the final enclosure heights. Enclosures and oxygen free high conductivity copper pinch-off tubing were machined at Bendix then cold formed together. These assemblies were then vacuum brazed using 82% gold, 18% nickel alloy at Aerobrazo, Inc. Leak testing of the final assemblies demonstrated less than 1×10^{-8} STD CC/SEC leak rates.

BRIDGE

The TMXO mechanical design utilizes either one or two mica bridges for support of the internal electronics package. The number of bridges as well as their configuration is based on heat transfer analysis and vibration testing. Fabrication of the mica bridges has been accomplished at Bendix. However, these .010 inch thick pieces have not been successful in fulfilling their design purpose. (See heat transfer and vibration testing sections for details.) Besides structural problems,

there are still concerns with vacuum maintainability when utilizing mica. Outgassing data is scarce and typically, published results disagree. Most radio tubes use mica as a bridge but before pinch off outgassing temperature is usually around 500°C. TMXO is not so fortunate since a maximum temperature of 150°C must not be exceeded. Considerable effort will be expended in this area to resolve the problem.

GETTER

In order to maintain vacuum of 1×10^{-4} torr or lower, TMXO will use a zirconium/graphite getter. SAES ST 171/LHI/4-7/200 is a room temperature getter that is activated by passing a current of 3 Amps through its internal heater while under vacuum. The getter heats up to 900°C and releases hydrogen. Uncontaminated getter material migrates from the bulk of the getter to its outside perimeter upon activation. If after a period of time the vacuum is degraded by outgassing the getter may be reactivated and hard vacuum once again achieved. A table of gas specie versus pumping capacity is seen below:

GAS SPECIE	PUMPING CAPACITY (CC-TORR)
H ₂ O	25
N ₂	2.5
O ₂	50
H ₂	1350
CO ₂	5

(2) HERMETIC SEALING AND VACUUM INVESTIGATIONS

WELDING

Both of the TMXO enclosures will be electron-beam welded at Ebtec in Agawam, Mass. Tooling is complete and sample piece parts were sent for weld schedule development. Along with these sample parts, two vacuum headers with glass feedthroughs were also sent. One of the headers had glass seals within .015 inch of the weld zone. All parts were leak tested after welding

with no leaks detected. As a result, the alternate header design with feedthroughs removed from the weld zone has been eliminated.

VACUUM INVESTIGATIONS

Initial plans included assembly of an appendage pump to the TMXO through a stainless steel tee fitting (See Figure #11) so that outgassing data could be taken. It was determined that this approach was unreliable either due to outgassing of the tee's viton gaskets or leaks in the system. Additional equipment was ordered from Varian. A system was designed (See Figure #12) consisting of a valve, ion pump, and ion gage, whereby, a TMXO could be attached and pressure monitored. The system is evacuated and baked out. Pressure versus time data is recorded to determine background outgassing. TMXO is then attached and the measurement repeated. The difference in the data being outgassing contribution of TMXO. Plans also include pressure versus time measurement before and after the getter is activated so that the getters pumping capabilities may be characterized.

Experiments with the copper pinch-off has shown this technique for final tip off to be very reliable.

(3) ASSEMBLY PROCESS DEVELOPMENT

Ashland Chemical Co., has been contracted to electropolish the headers and enclosures. Samples that were polished at Ashland were sent to Bendix Research Labs. where emissivity measurements were made. The data indicates little change in emissivity: unpolished as rolled (.079) and electropolished sheet (.077). When polishing brazed assemblies a black oxide formed in the areas of the braze alloy. Consequently, Kovar header plates and enclosures will be polished prior to brazing. Headers with glass feedthroughs were unaffected by polishing.

All the inhouse welding of assemblies have been developed and few problems have been experienced.

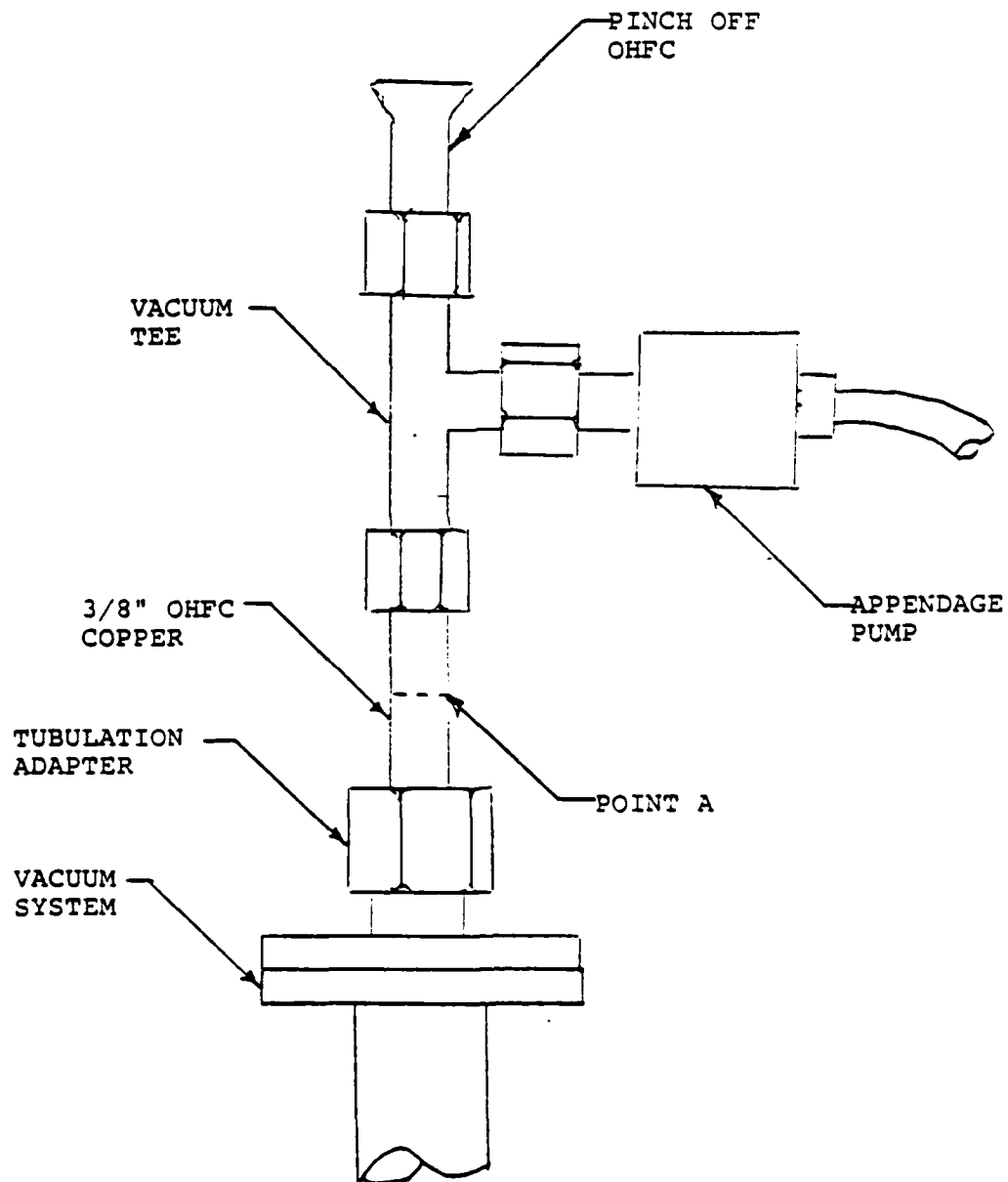


Figure 11. Appendage Pump Attachment

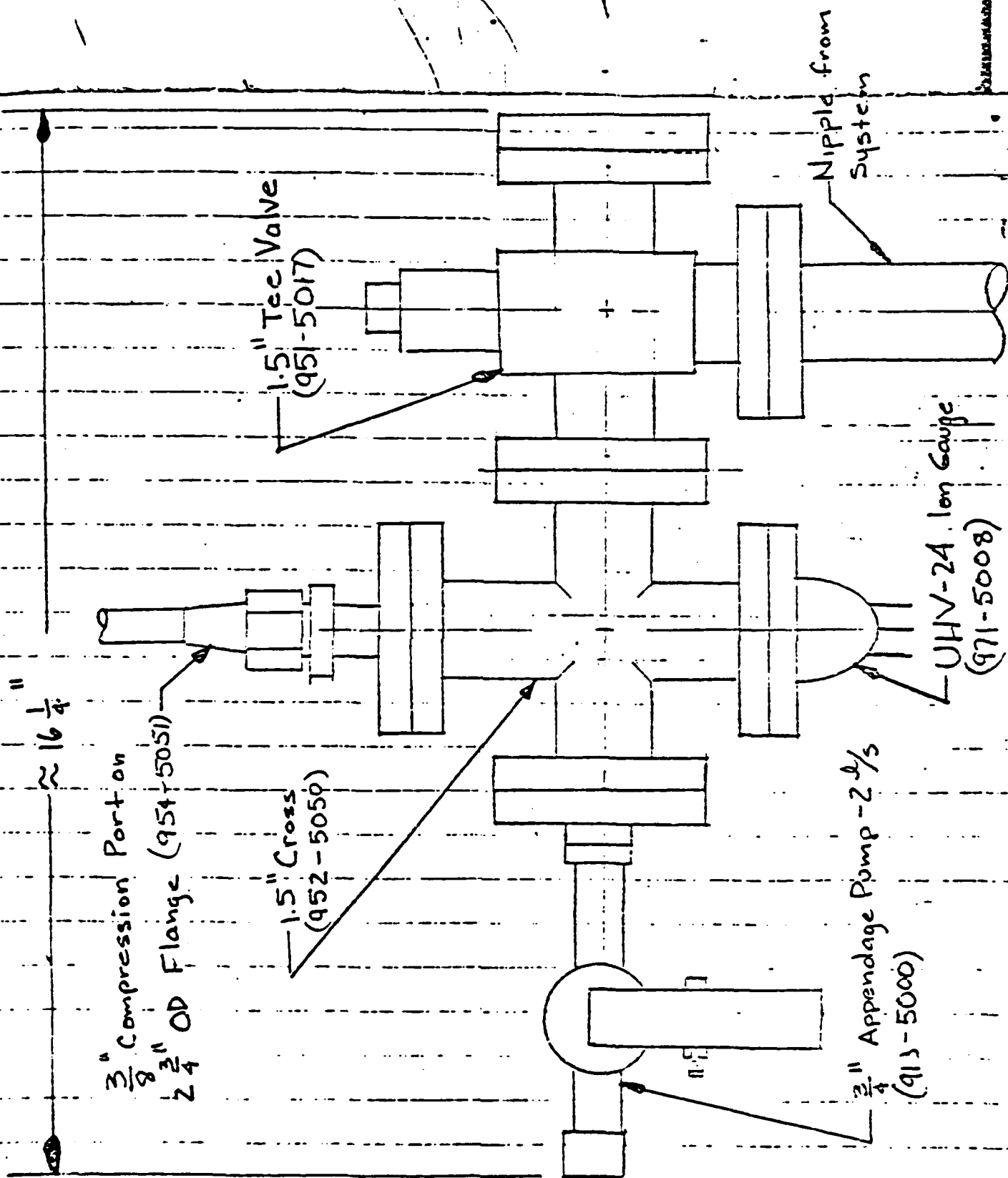


FIGURE 12. PRESSURE MEASURING SYSTEM

Processes for cleaning the TMXO piece parts have been developed. These include vapor degreasing; ultrasonic cleaning in acetone, trichloroethane, and methanol; and vacuum outgassing prior to assembly. An outgassing chamber has been designed and fabricated so that parts may be baked on the clean Varian vacuum system instead of the diffusion system previously reported.

The Quartz crystal resonators have been successfully plated at Vectronics Microwave. The process consists of Sputtering 200-500Å of chrome, then sputtering 5000 Å of Copper, electroplating .2 - .3 mils of copper and finally flashing electroless tin. This metal system allows easy soldering of the BeO heat spreaders to the resonator covers with tin-lead solders. Fixturing for the assembly of the microelectronic package as well as the overall TMXO package has also been developed.

(4) VIBRATION TESTING

In order to determine TMXO's response to vibration in a timely manner, a mechanical model was constructed. All parts were simulated, as close as possible, to the final TMXO configuration. The first model incorporated a ceramic header with .018 inch diameter Kovar wire which had been annealed and one mica bridge. Horizontal vibration per MIL-STD-810C (Curve M) produced resonance at 90 Hz. The mica points which were severely distorted, provided little support to the outside enclosure and rattling occurred. A second pass using stainless steel tubes and a new mica bridge was tried but this too was unsuccessful. Again, the mica bridge tips broke or distorted. Future plans include vibration testing with two mica bridges, and possibly a material search for a suitable replacement for the mica.

THERMAL ANALYSIS

Work has continued on the lumped, 5 node, 10 conductor model to allow an evaluation of the thermal performance based on various aspects of the design. Figure 13 shows the nodes and conductors. The nodes are defined in the figure and the resistors are:

- R_1 = Conductance through the kovar wires
- R_2 = Radiation from the electronics assembly to the inner case
- R_3 = Conductance through the top mica spacer to the mica tips
- R_4 = Radiation from the sides of the inner case to the outer case
- R_5 = Conductance through the top mica tips
- R_6 = Radiation from the top and bottom mica spacers to the outer case
- R_7 = Conductance through the kovar wires and straps from the crystal package to the inner case header
- R_8 = Not used
- R_9 = Conductance through the bottom mica
- R_{10} = Not used
- R_{11} = Gas conduction inner case
- R_{12} = Conduction through bottom mica tips

Initial runs of this model with R_{11} omitted (representing the inner chamber at a pressure $< 1 \times 10^{-4}$) indicated a critical thermal path existed at R_7 . To determine the impact, runs were made with the assumption that the welds at the straps could be made nominally in the middle and at the worse case tolerance conditions. The results are shown in Figure 14 which indicates a large variation in power at a given crystal temperature. The lower set of curves shows

TMXO - Thermal Model

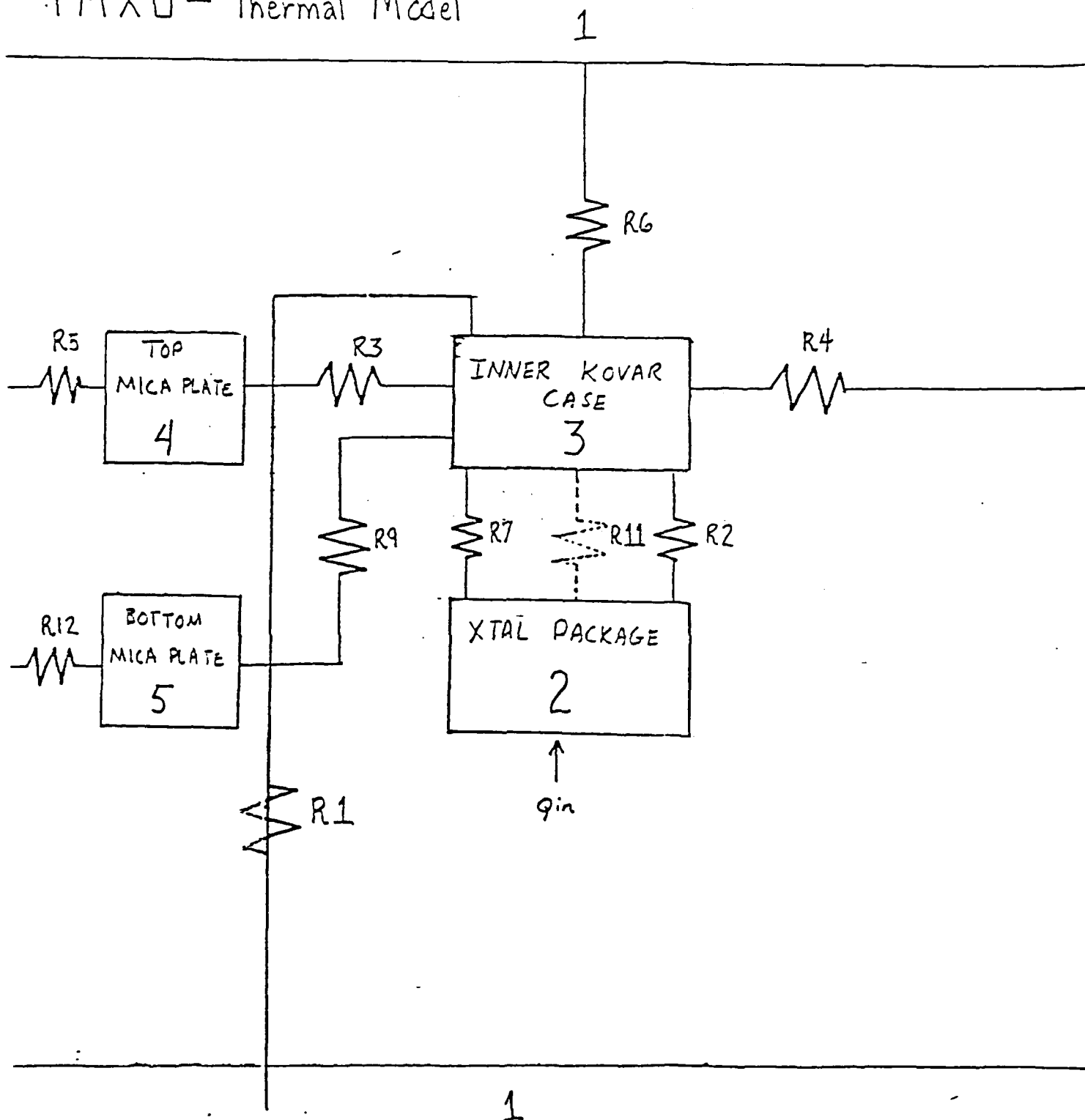
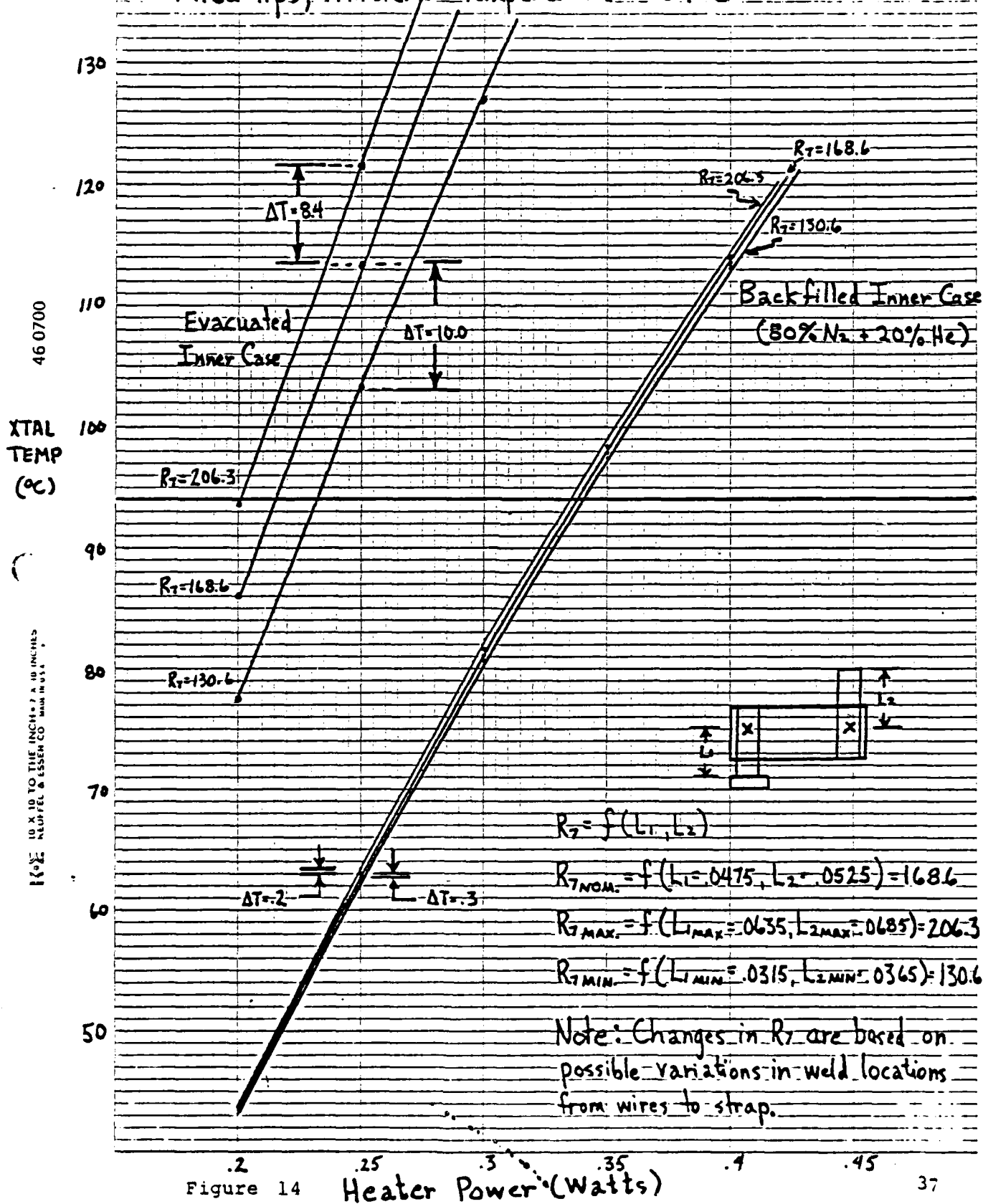


Figure 13. TMXO Thermal Model

Graph of Heater Input Power vs. Crystal Temperature With
5 Mica Tips, Ambient Temperature = -54°C

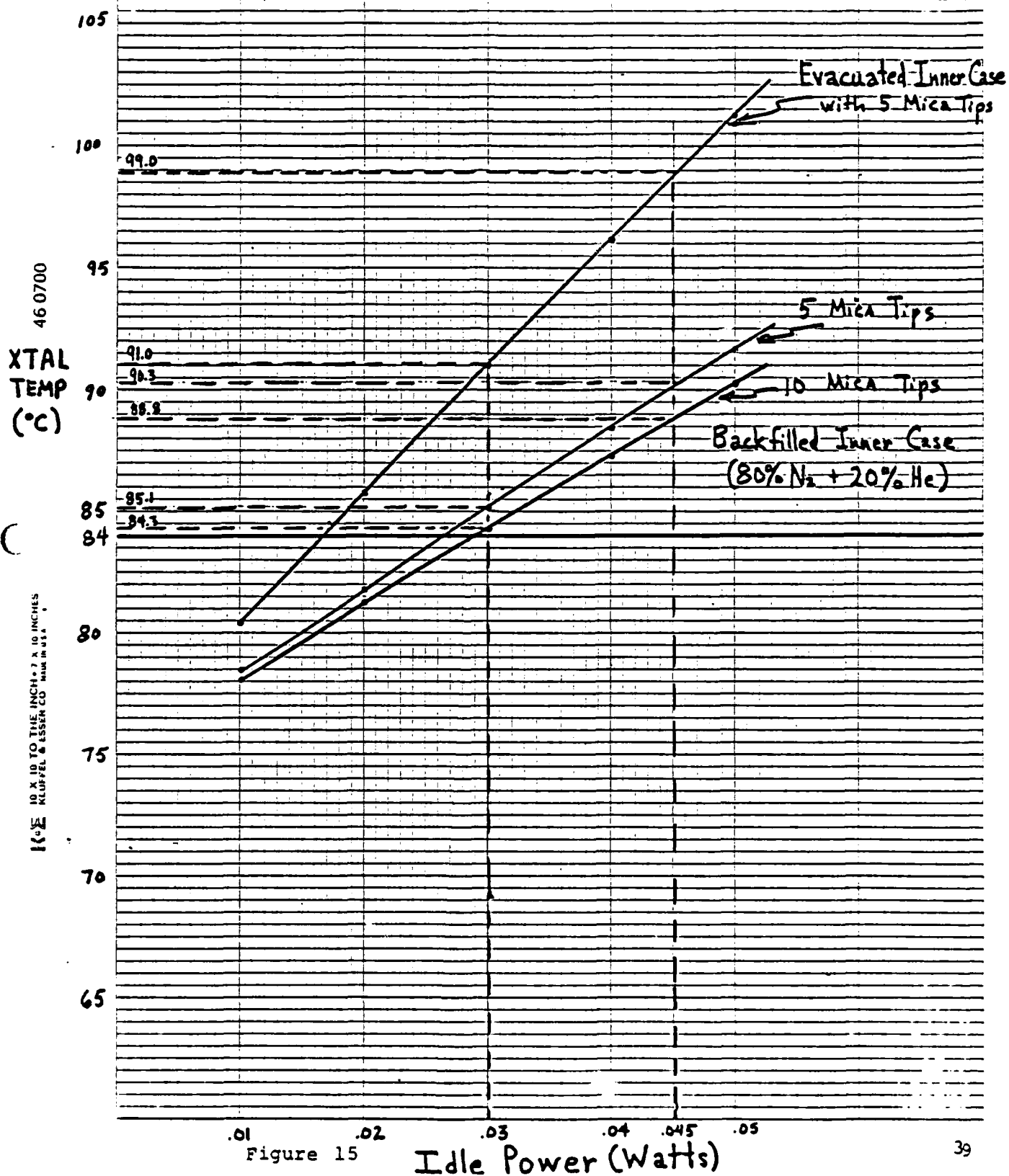


that the assembly techniques and normal tolerances reduce this variation when the inner case is backfilled with a mixture of 80% Nitrogen and 20% Helium. The impact on the thermal performance as shown in the graph, is the increase in power required at the low ambient. In addition, control of the pressure in the inner case to be consistently below 1×10^{-4} Torr is anticipated to be difficult due to the materials used to produce the electronics, i.e. solders, inks, etc. Since the thermal conductivity of gases typically varies substantially with pressure between 10 Torr and 1×10^{-3} Torr and is effectively unchanged above 10 Torr and due to the variations that might be expected as described above, a consistent producible design can be expected if the inner case is backfilled with a mixture of 80% Nitrogen and 20% Helium to a pressure of 10 torr. The gas mixture and pressure was selected to allow leak detection of the package and to prevent variations in high vapor pressure components and contaminants from impacting on the thermal properties of the package. Additionally, backfilling to the pressure shown, as opposed to atmospheric pressure, will cause less impact on the outer chamber vacuum should a minute leak exist.

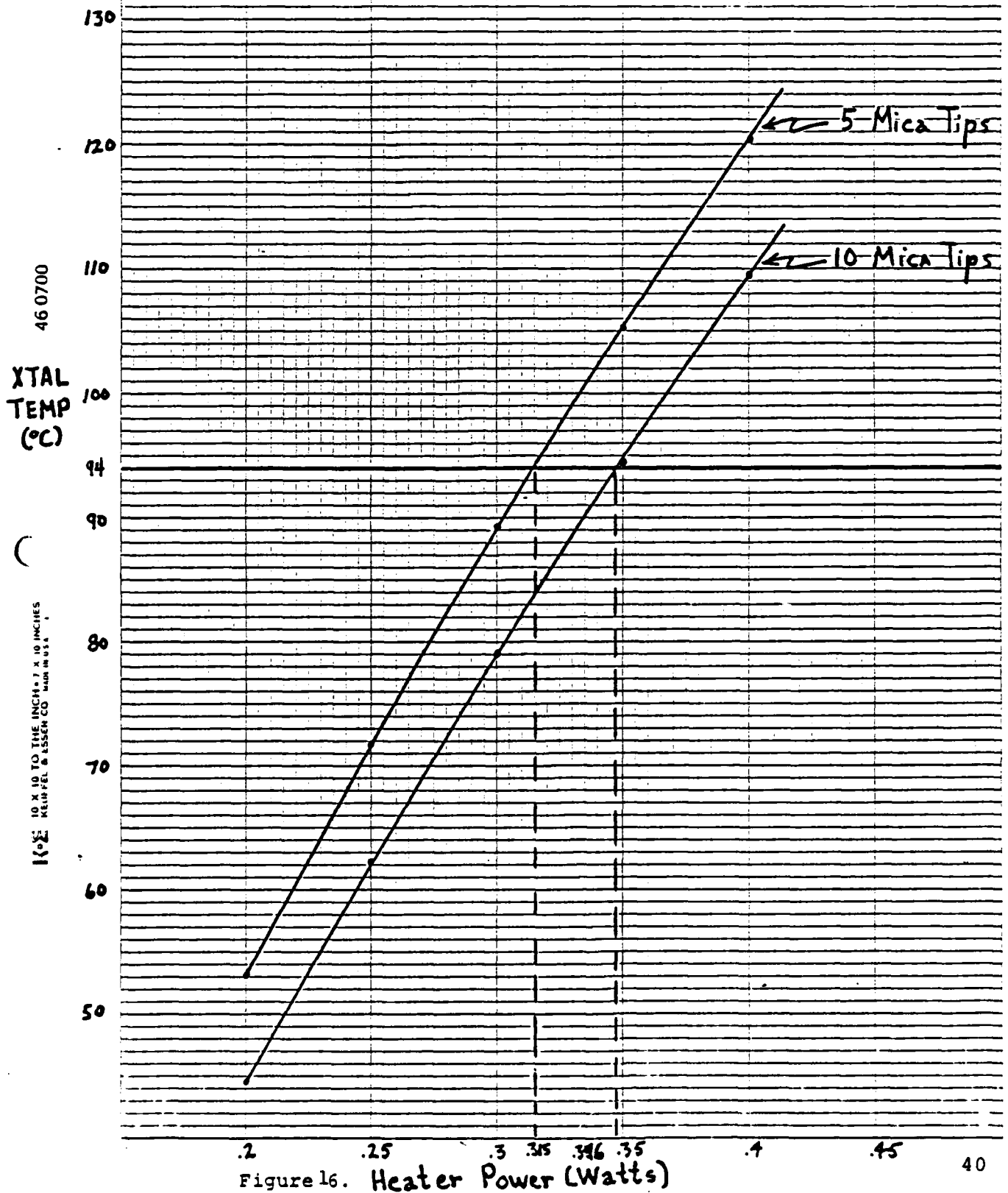
An additional benefit resulting from backfilling the inner case is that the minimum crystal turn point, at the high ambient, is reduced to 85°C as shown in Figure 15. The evacuated case, at the same power, calculates to be 91°C.

Figures 16 and 17 indicate the expected crystal temperatures at -54°C ambient and -40°C ambient as a function of input power. These plots are based on utilizing two .010" thick mica support spacers to enhance the vibration and shock resistance of the system. The thermal performance is impacted heavily by the quantity and physical shape of the mica; plans are to provide for attachment of mica supports at the top, bottom and middle of the electronics package to allow the option of selecting the minimum to be used based on vibration tests. Efforts are continuing to evaluate the impact of various reproducible methods that could be employed to satisfy the two extreme temperatures while retaining adequate mechanical strength.

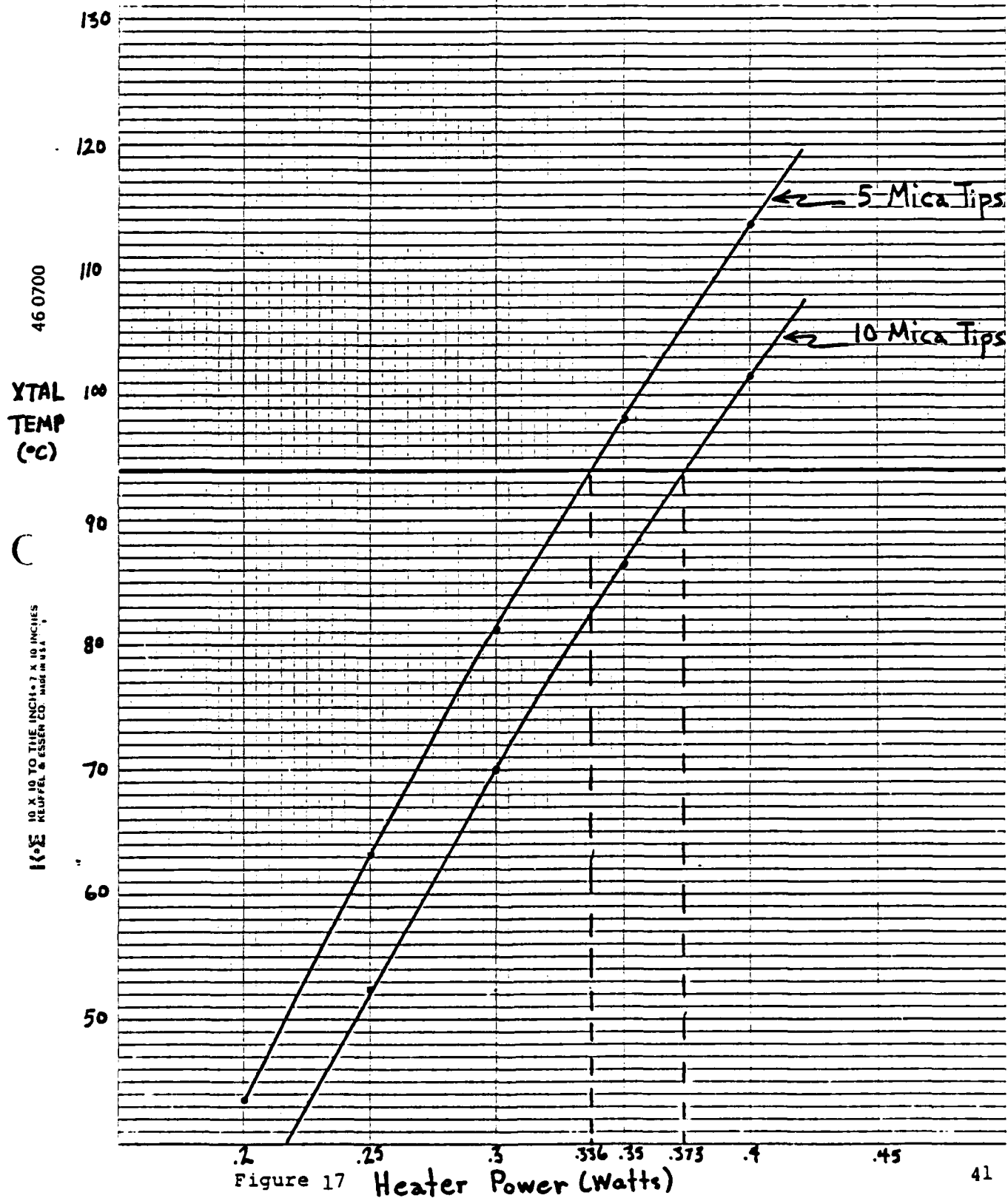
Graph of Idle Power vs. Crystal Temperature With Ambient Temperature = +75°C



Graph of Heater Input Power vs Crystal Temperature With
Backfilled Inner Case (80% N₂ + 20% He), Ambient Temp = -40°C

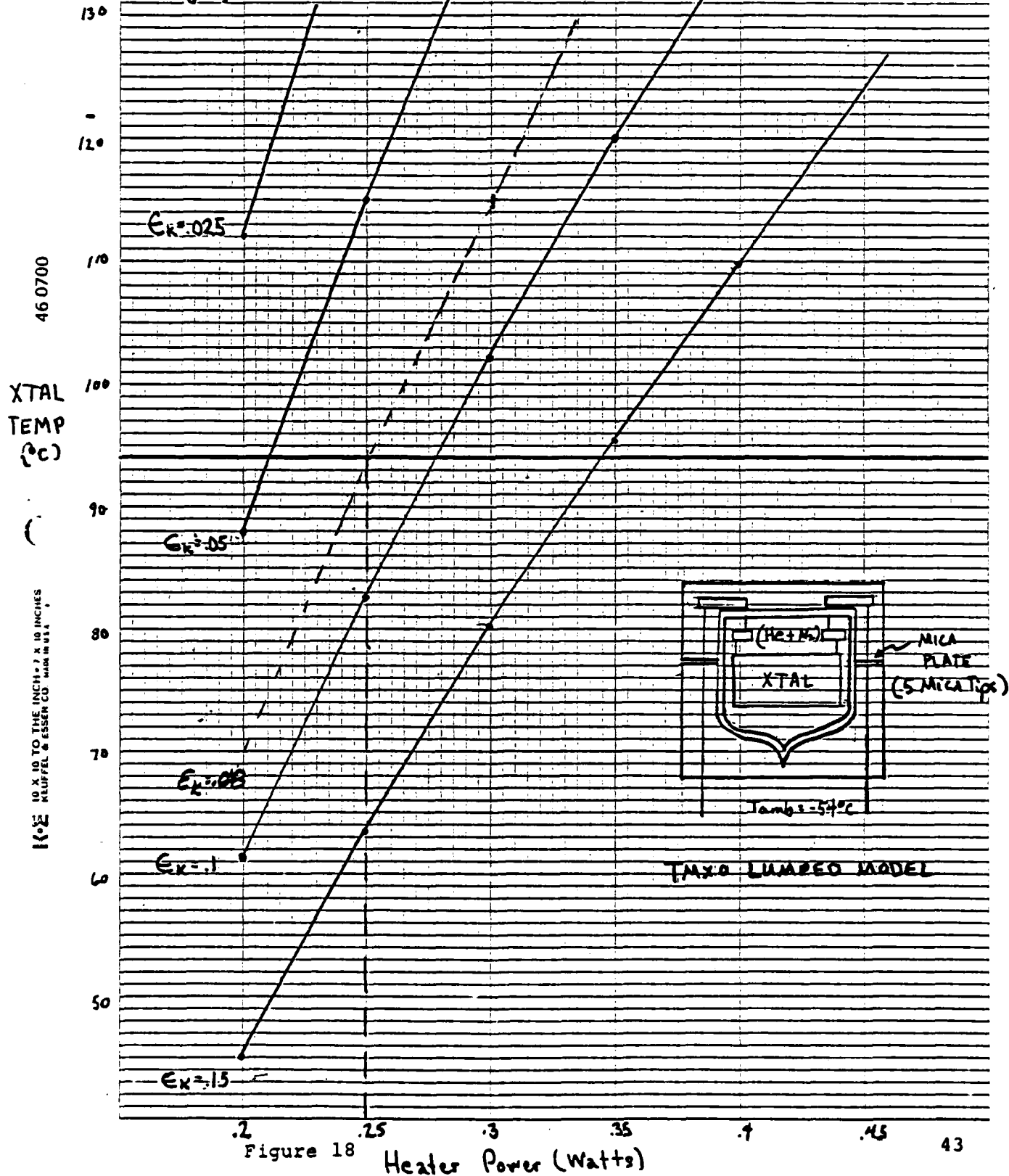


Graph of Heater Input Power vs. Crystal Temperature With
Backfilled Inner Case (80% N₂ + 20% He), Ambient Temp = -54°C



Figures 18 and 19 show the improvement that can be expected with a single mica bridge design, and the impact of thermal radiation on the performance. To allow comparisons, the emissivity used in the previous figures 14, 15, 16 and 17 was 0.1.

Graph of Heater Input Power vs. Crystal Temperature With Backfilled Inner Case (80% N₂ + 20% He); Ambient Temp = -54°C; for Varying Korar Emissivities ϵ_K .



Graph of Idle Power vs. Crystal Temperature With Backfilled Inner Case (80% N₂ + 20% He); Ambient Temp = +75°C; for Varying Kovar Emissivities ϵ_k

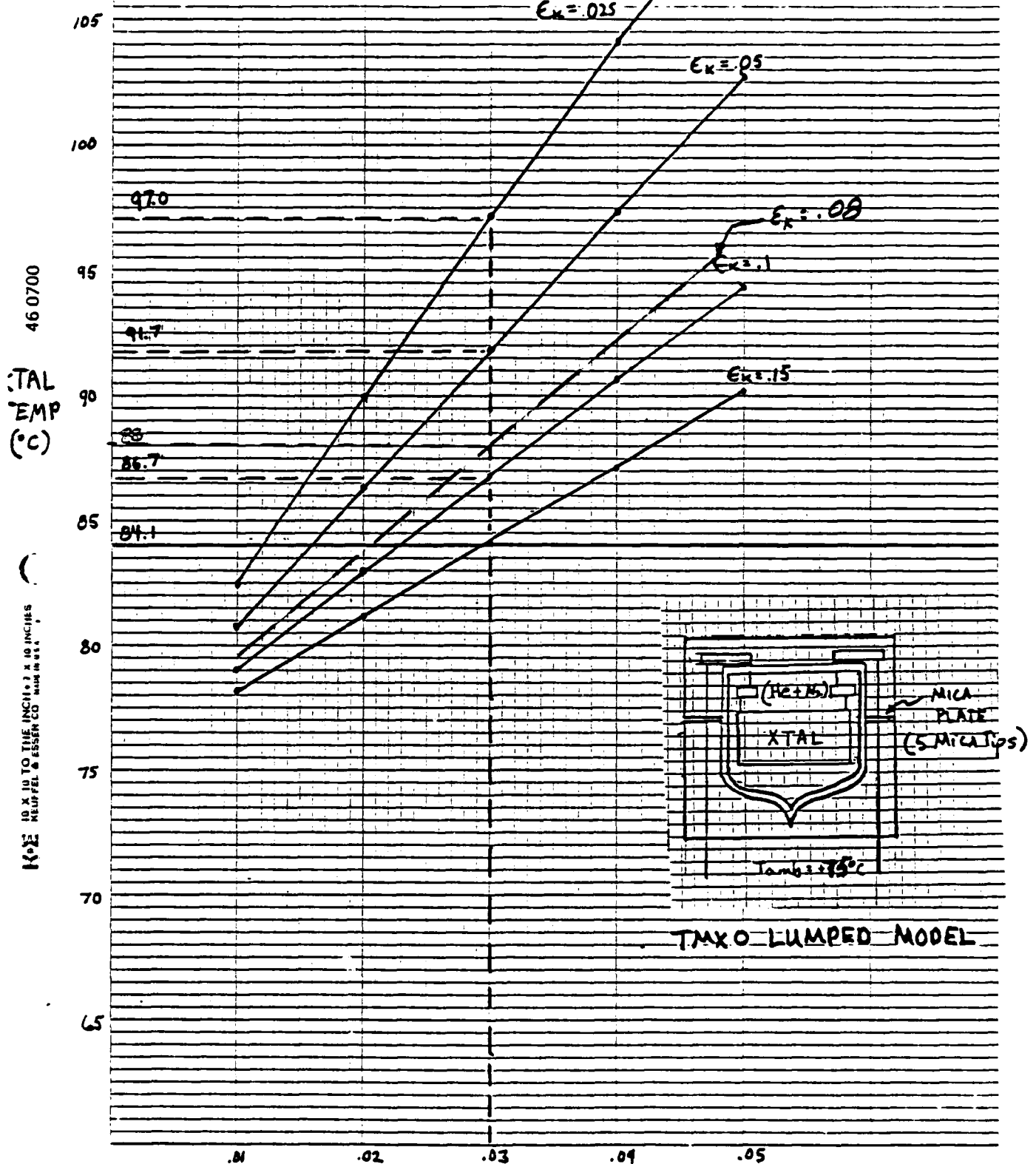


Figure 19 Idle Power (Watts)

TMXO PROTOTYPE

An electrically functioning TMXO has been build. All processing for the prototype, with the exception of the E-beam welding of the enclosures was done at Bendix. This unit utilized the leak tested glass feedthrough headers made at Airpax. Instead of mica, a decision was made to utilize a alumina spacer at the top of the electronics package to provide insulation for the welded interconnect straps. Electron beam welding of the prototype was accomplished with no difficulties. However, two leaks in the glass feedthroughs were detected. One occurred in the electronics header and one occurred at the getter feedthrough in the vacuum header. Both of these leaks were probably the result of stress during the welding of the straps or getter to the feed-throughs rather than the E-beam welding, since both feed-throughs were well removed from the E-beam weld zone. Subsequent units will incorporate ceramic feed-throughs which should be more resistant to stress damage.

Both leaks were repaired with TORR-SEAL, a low vapor pressure epoxy manufactured by Varian. This unit will be attached to the pressure measuring system discussed in the previous vacuum section where performance data may be recorded.

3. CONCLUSIONS

As a result of the work performed during this period, we conclude:

- (1) In order to achieve specified long term stability performance with the fundamental crystal oscillator, the crystal finishing tolerance will have to be reduced, and the crystal operated at larger values of load capacitance.
- (2) The crystal sensitivity to gravity forces will have to be reduced; for the fundamental A/T cut units, the G-sensitivity is a significant contributor to frequency variations.
- (3) The short term stability of the 10 MHz third overtone units received so far is inferior to the better fundamental units, and is not within specifications.
- (4) The thermal analysis, performed with a more simplified model, indicates the thermal design is converging on a successful configuration.
- (5) The materials and processes selected together with the designated getter are capable of providing the vacuum integrity necessary for the thermal performance specified.

4. FUTURE PLANS

The final six month period will be used to complete the following aspects of the TMXO Program.

- (1) Construction and evaluation of prototype units.
- (2) Correction of deficiencies through design modifications.
- (3) Assembly and test of remaining units.
- (4) Completion of documentation.

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